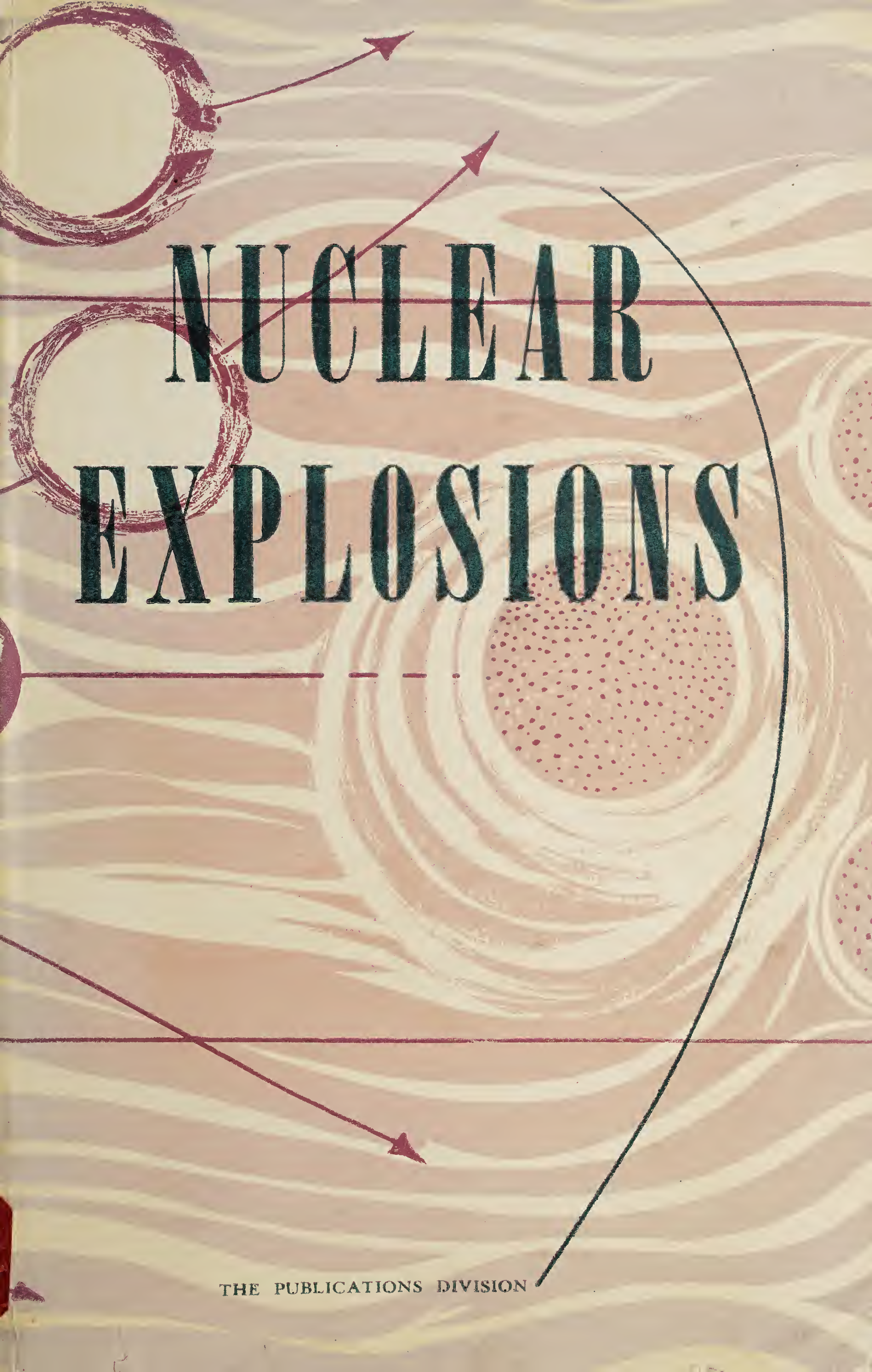
NUCLEAR EXPLOSIONS



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In this book an attempt has been made to describe in broad terms the physical and biological effects of nuclear explosion. Beginning with a brief account of the relevant scientific facts and principles, it discusses among other things the radiological effects of high-yield fission explosion which liberates energy equivalent to millions of tons of conventional explosives.

A book like this, covering as it does so vast a subject, is bound to be incomplete; but care has been taken to state the essential facts. It is hoped that it will be of interest both to scientists and laymen alike.

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NUCLEAR EXPLOSIONS
AND THEIR EFFECTS

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NUCLEAR EXPLOSIONS
AND
THEIR EFFECTS

FOREWORD BY
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FOREWORD

About a year ago I suggested to the Defence Science Organisation of the Government of India that an objective study might be made with the material available of the consequences of the use of nuclear, thermonuclear and other weapons of mass destruction. Such a study could not, in the circumstances, be complete, as much of the information was considered secret. Nevertheless, I thought that it would enable us and others to form some picture of what modern war was likely to be. There have been frequent references in the newspapers and in periodicals to the result of nuclear explosions and some official publications have also been issued on this subject by various Governments. But I was not aware of any connected account and I thought that such an account, even though incomplete, would be useful.

Dr. D.S. Kothari of our Defence Science Organisation was specially entrusted with this task. With him were associated Dr. Homi Bhabha who is in charge of our atomic energy work, and Dr. V.R. Khanolkar, the Head of the Cancer Research Institute in Bombay. The preparation of this study was delayed because of the Conference on the Peaceful Uses of Atomic Energy held in Geneva last year. That Conference brought out many facts which till then had been unknown to the public.

The chief burden of preparing this study has thus fallen on Dr. Kothari. Dr. Homi Bhabha, in spite of the heavy burden he carries, has given substantial help. A number of our younger scientists connected with the Defence Science Organisation and the Atomic Energy Department have also given valuable help.

I have tried to restrain our scientists from being too technical. I have not succeeded wholly, but I think that this study will be of value even for non-scientific readers and the public generally. It will give some idea of the world we live in and even more so of what the fate of the world is likely to be if we start playing about with nuclear warfare. I suppose that no one, not even the great experts in this new science, knows definitely what the full results of Hydrogen Bomb explosions will be. Enough is known, however, to give us some kind of a picture of a war in which these weapons are used. War is associated with death. We have now to face death on a colossal scale and, what is much worse, the genetic effects of these explosions on the present and future generations. Before this prospect, the other problems that face us in this world become relatively unimportant.

But even without war we have what are called nuclear test explosions which, in some measure, spread this evil thing over large parts of the world. These explosions continue in spite of the dangers inherent in them.

I trust that this study, brief and incomplete as it is, will be of some use in directing peoples' minds to the dreadful prospect of war in the nuclear age and to the dangers of continuing nuclear test explosions.

New Delhi,
June 20, 1956

Jawaharlal Nehru

PREFACE

This book attempts to describe in broad terms the physical and biological effects of nuclear explosions. A brief account has also been included of the relevant scientific principles and facts. Special attention has been given to the radiological effects of high-yield fission explosions which liberate energy equivalent to millions of tons of TNT.*

Considerable open literature on the subject is already available, though widely scattered in physical, biological and other publications. Particular reference should be made to the literature released on the subject by the United States Atomic Energy Commission, publications of the Japanese scientists, and the Proceedings of the International Conference on the Peaceful Uses of Atomic Energy held in Geneva in August 1955. The report on the hazards of nuclear and allied radiations issued in the middle of June by the UK Medical Research Council, and the report on the genetic effects issued by the United States National Academy of Sciences were, unfortunately, not available in time to be made use of in the present study.

A book such as this, covering a vast subject, is bound to be discursive and not entirely free from errors; but care has been taken to state the essential facts. It is hoped that the book will be of interest to scientists and others generally. The way to ensure that the new atomic knowledge is used for the good of man is to make us aware of the peril that faces us if this knowledge is not rightly used.

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* Chapters V and VI are devoted to the description of the effects of these high-yield explosions and may be read independent of the rest of the book.

Appendices to Chapters II and V are intended to provide additional scientific and technical information on some of the important points discussed in the text.

Special mention should be made of M.L.N. Sastri, A. Nagaratnam, B. C. Ray Sarkar and M.P. Murgai of the Defence Science Laboratory, K.S. Singwi and A.R. Gopal Ayengar of the Department of Atomic Energy, who have assisted in the preparation of this book.

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CHAPTER I

INTRODUCTION

Mankind has for long made use of the energy of flowing water and the energy given out in the burning of wood and coal. The first is an instance of gravitational energy and the second of chemical energy (which is essentially electrical in origin). In recent years an entirely new energy process, roughly a million times more powerful than any chemical process, has been discovered. The source of this energy lies in the force, called *nuclear force*, which operates between the constituents, protons and neutrons, of atomic nuclei. It should be observed that, unlike gravitational and chemical energy, the harnessing of nuclear energy — also called *atomic energy* — demands deep insight and considerable progress in *fundamental* science as distinct from the empirical arts and crafts.

The modern epoch in physics may be said to have begun with the discovery — almost accidental — of X-rays in 1895 by the German physicist Roentgen. This initiated a period of unprecedented progress in physical science. In seeking a possible connection between phosphorescence and X-rays the French physicist Becquerel chose, by signal good fortune, uranium nitrate as the substance for investigation, and was led, unexpectedly in 1896, to the discovery of radioactivity. This, in its turn, soon led to the discovery of radium by Pierre and Mme. Curie. In 1905, Einstein enunciated the theory of special relativity and as a consequence from it established the equivalence between mass and energy. The great work of Rutherford on radiations (named by him as alpha, beta and gamma rays) emitted from radioactive bodies eventually led to the concept of the atom as made up of a central core, the nucleus, with electrons revolving around it—'a solar system in miniature'. Bohr with uncanny insight incorporated the quantum hypothesis of Planck and Einstein into the Rutherford atom-model and thus formulated his far-reaching quantum theory of the atom. In 1919, Rutherford, for the first time, achieved disintegration of an element (nitrogen) by bombarding it with alpha particles. A beautiful cloud-chamber photograph of the same process was soon provided by Blackett. Chadwick, working in Rutherford's laboratories, discovered the neutron in 1932. In the same year and in the same laboratory Cockcroft and Walton brought about the first artificial nuclear transmutation by bombarding lithium with protons accelerated to less than a million volts. New discoveries followed in rapid succession.

The phenomenon of uranium fission was discovered by the German physical chemists Hahn and Strassman in 1938. The extraordinary significance of the discovery was soon realized, and led to a period of intense activity in the study of atomic nuclei. By 1940 more than a hundred papers had appeared on this subject. Soon after, the whole subject went 'underground' and no further reference appeared in open scientific literature till the end of the war.[1]

It should be observed that though the basic discoveries leading to the realization of atomic energy came practically all from Western Europe, it was not Western Europe but the USA (soon followed by the USSR) which, with its colossal industrial and scientific resources, was the first to harness this basic knowledge to practical ends.

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[1] An excellent review of the earlier work was given by L.A. Turner in *Reviews of Modern Physics*, **12,** 1 (1940). A review of the post-1940 work was given in *Progress in Nuclear Physics*, **II,** 1952.

Hiroshima-Nagasaki Bombs

On August 2, 1939, Albert Einstein wrote his now famous letter to President Roosevelt drawing attention to the possibility, as then indicated by some work of Fermi and Szilard, of utilizing the phenomenon of uranium fission for the construction of extremely powerful (weight for weight) bombs of a new type — a million times more powerful than conventional bombs. " A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory ", said Einstein. The US Government decided to explore this possibility seriously; it was particularly guided by the thought that Germany probably was already engaged in this field, and if it succeeded, the consequences would be catastrophic for the Allies.[2] The first successful realization of a (slow neutron) fission-chain reaction in the graphite-pile built in a converted squash-court of the University of Chicago's Stagg Field was achieved by Fermi on December 2, 1942. It is a landmark in the history of nuclear science. It led to the construction of a gigantic plant at Hanford on the banks of the Columbia river for the production of plutonium. Following the work of Urey on diffusion, a plant for the production of uranium 235 from natural uranium was built at Oak Ridge. Another plant at Oak Ridge produced uranium 235 employing the principle of electromagnetic separation. The designing of a workable ' atomic bomb ' was entrusted to the new Los Alamos Laboratory (New Mexico) working under the leadership of Robert Oppenheimer. Three bombs were produced by the middle of 1945. One made of plutonium was tested on the ground at Alamogordo sands on July 16, 1945. The other two were dropped on Hiroshima and Nagasaki on August 6 and 9, 1945.

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[2] It is interesting to recall that the first Government grant was a sum of about $6,000. By 1945 the whole project had swelled to about 2,000 million dollars.

Truman, the then President of the USA, writes in his Memoirs (1956) : " One event occurred in 1945 of such magnitude that it was to revolutionize our relations with the world and usher in a new era for humanity, the fruits and goals and problems of which we cannot even now fully grasp. It was the atomic bomb."

The Hiroshima bomb was of uranium 235 and the Nagasaki one was of plutonium 239. The two bombs were detonated at a height of about 2,000 feet in order to emphasize the devastation caused by the blast and heat of the explosion.

The bomb on Hiroshima was dropped by a B-29 aircraft at 8-15 on the morning of August 6, 1955, and to quote from the *US Strategic Bombing Survey Report, Part V*:

" Most of the industrial workers had already reported to work, but many workers were *en route* and nearly all school children and some industrial employees were at work in the open on the programme of building removal to provide fire-breaks and disperse valuables to the country. The attack came forty-five minutes after the ' all clear ' had been sounded from a previous alert. Because of the lack of warning and the populace's indifference to small groups of planes, the explosion came as an almost complete surprise and the people had not taken shelter. Many were in the open, and most of the rest in flimsily constructed homes or commercial establishments."

Hiroshima had a total of 75,000 houses. About 7,000 houses were totally destroyed and 55,000 were completely burnt. More than 90 percent of all the houses suffered complete to partial destruction. The Nagasaki bomb was more powerful (15 percent greater radius of destruction) than the Hiroshima one, but on account of the unevenness of the terrain the damage caused was relatively less. The total number of men killed in Hiroshima and Nagasaki was over 100,000.

The area of destruction and the number of casualties caused by the two atomic bombs are given in Table I. The last column of the table gives for comparison the destruction caused by conventional (high explosive and incendiary) bombs. It refers to the Tokyo raid of March 9, 1945, when 279 US planes dropped about 1,700 tons of bombs.

TABLE I

	Hiroshima Atomic Bomb	Nagasaki Atomic Bomb	Tokyo 1,667 tons TNT and Incendiary
Dead	78,150	23,753	83,000
Missing	13,983	1,924	
Injured	37,424	23,345	102,000
Otherwise Afflicted	235,656	89,025	
Total	365,213	138,047	
Population per sq mile	35,000	65,000	130,000
Sq mile Destroyed	4·7	1·8	15·8

Note :—The figures for the casualties in Hiroshima and Nagasaki are taken from the recent publication, *Atomic Bomb Injuries*, edited by the Japanese Preparatory Committee for Le Congrès Mondial des Médicins pour l'Étude des Conditions Actuelles de Vie, (Chief Editor : N. Kusano) Tokyo, 1953. The figures of population and area destroyed, and also all the figures in the last column are taken from the USAEC publication, *The Effects of Atomic Weapons*, 1950.

Total Casualties in Wars I and II

The total number of casualties — killed, missing and wounded, both military and civilian — can be roughly estimated at about 40 million for each of the two World Wars. The figure for World War I includes deaths due to epidemics directly attributable to war or as a consequence of it. Battle casualties formed only a small fraction of the total casualties. In fact it was only in World War II — and this is the first instance in history — that deaths in the fighting services caused by epidemics and septic wounds were less than deaths in battle. This was due to great advances in medical science, the single greatest thing being the discovery of penicillin. For example, in the US Army in World War II the number of deaths in battle was 237,000 as against 65,000 non-battle deaths.[3] The figures for World War I were 51,000 battle deaths and 56,000 non-battle deaths. The corresponding figures for the Mexican Civil War were 1,557 and 11,377 respectively.

Total Explosive Energy Released in War II

The explosive energy of the Hiroshima or Nagasaki A-bomb was nearly equal to that of 20,000 tons of chemical explosive, say TNT. (We thus speak of it as a 20 kiloton A-bomb). This represented more than a thousand-fold larger explosive energy than that attained in the biggest bombs of the time, based on conventional explosives. The total weight of the bomb (including tamper, parachute etc.) was about 5 tons, the weight of the fissile material (uranium 235 or plutonium 239) being of the order of 50 kilograms. It should be noted that though the explosive energy released in the A-bomb is equal to that of 20,000 tons of TNT, the area of destruction is about only *one-tenth* of what would be achieved if 20,000 tons of TNT were scattered on the target in the form of conventional bombs (say 2,000 lb bombs). This happens because the A-bomb, as it were, fritters away a large part of its explosion energy by ' over-destroying ' the target area in its immediate vicinity. The structural damage is mainly caused by blast, and the area of destruction is proportional to $E^{\frac{2}{3}}$ (and not E), where E is the energy of explosion.

Great though the explosive energy of the Hiroshima-Nagasaki atomic bombs was, yet it was only a very small fraction of the total explosive energy released during the six years of World War II. The total weight of explosives consumed during the war was about 5 million tons. The weight of bombs dropped on Germany alone during the war was about 1·3 million tons, killing approximately half-a-million people, *the bomb-load per fatal casualty thus being* 2·6 *tons.* It would be true to say that the explosive energy released during World War II far exceeded the total explosive energy released during all the earlier wars, including World War I. And yet this energy is a small fraction of that liberated in a single thermonuclear explosion.[4] Such has been the progress, if progress be it called, in the field of military applications of nuclear energy during this ' decade of peace '. *Thus, for instance*, *each of the test explosions conducted by the USA in March 1954 and May 1956, and by the USSR in November 1955 produced far more explosive energy than the total explosive energy released by mankind in all its history.* And yet for the thermonuclear weapons now in development and production the direct effects of the explosive energy sink into relative insignificance when compared with their radiological effects (see Chapter V).[5]

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[3] G. W. Beebe and M. E. De Bakey, *Battle Casualties*, 1952.

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[4] The mechanism of fission and thermonuclear processes is dealt with in Chapter II.

[5] A rough index of the production of explosives is provided by the production of chemically-bound nitrogen, this being the basic constituent of fertilisers and explosives. The discovery by Haber and Bosch in 1913 of producing nitrogen from air, apart from laying the foundation of a great world industry, made the most vital contribution to the German war effort in World War I when the Allied blockade cut off the supply of Chilean nitrates needed both for explosives and fertilisers. The total production of synthetic nitrogen for the years 1915-19 can be taken as 3 million tons as against about 19 million tons during the period 1939-45.

Incidentally, it may be mentioned that up to about the middle of the 19th century, India (mainly Bihar, U.P., and the Punjab) was "almost the only source of saltpetre". "Prior to the Indian supply becoming available, saltpetre was obtained in England, at any rate, by the removal and treatment of earth from the neighbourhood and even the interior of dwelling places, under the authority of the Crown, a measure which was often worked very oppressively. The

Fission and Thermonuclear Test Explosions

It is estimated that since the end of the last war altogether about eighty test explosions have taken place, at least nine being thermonuclear.

The first Soviet atomic (that is, fission) explosion took place in August 1949. It was first announced on September 23, 1949, by President Truman that the US Government had incontrovertible evidence that the Russians had detonated a fission device. This was doubtless a great achievement for the Russians. It marked the end of the US monopoly in fission weapons much sooner — at any rate, by a couple of years — than had generally been expected even in reasonably well-informed circles. The US Government immediately decided to go in for the *thermonuclear bomb* (the so-called *H- or super bomb*) and on January 31, 1950, Truman directed the Atomic Energy Commission to go ahead with the project on an all-out basis. This decision ended a long and tortuous series of discussions in the Atomic Energy Commission (with David Lilienthal as Chairman), and its General Advisory Committee (with Robert Oppenheimer as Chairman), where opinions on the speed and scale of the effort to go into the Super had been sharply divided. Much of this controversy is reflected in the pages of the great document of our times, the transcript of the *Oppenheimer Hearings, 1954.* It was on November 1, 1952, that the USA first tested at Marshall Islands in the Pacific Ocean a thermonuclear device (' Mike ').[6]

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discovery of a method of making saltpetre artificially from the nitrate deposits of South America and the German potash beds hit the Indian trade very hard, and not the less so that this discovery nearly synchronized with the imposition of an export duty of Rs. 2/- a maund by the Government of India in 1860."

The annual export, about 1860, of saltpetre from India was 5,000 tons. The people who did the extraction of saltpetre were called *nunias.* [From *The Report of the Indian Industrial Commission, 1916-18*].

[6] For an interesting account of the history of the project, see E. Teller, *Science*, **121**, 267 (1955).

The first Soviet thermonuclear test explosion took place in August, 1953. Special investigations (by the US Atomic Energy Commission) revealed that the Russian explosion had injected into the upper atmosphere appreciable quantities of Li^6. This showed that they had used lithium deuteride (Li^6H^2) in part (or very nearly total) replacement of the extremely expensive tritium for the fusion reaction.[7]

On March 1, 1954, the USA set off a powerful thermonuclear explosion at Bikini Atoll, the energy of the explosion being equivalent to about 15 million tons of TNT. This explosion is often referred to as the March 1954 Bikini Test. Another powerful fusion explosion was set off on March 26 at Marshall Islands. Possibly one or both of the March explosions contained Li^6H^2.

The Russians tested some thermonuclear devices in September/October 1954. In November, 1955, the Russians had a thermonuclear explosion about as powerful as the USA test of March 1954. The Russian explosion went further in one important respect. The ' device ' (dropped from an aircraft) was exploded high up in the air. It was the first case of an ' air burst ' ; *all previous thermonuclear explosions were ' ground bursts '* (Chapter V).

On May 21, 1956, the USA conducted their first ' air burst ' thermonuclear test explosion[8]. The device was carried in a B-52 jet bomber. The explosion is supposed to have taken place at an altitude of about 3 miles, the power of the explosion being roughly equivalent to 15 million tons of TNT.[9]

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[7] See for instance, P.M.S. Blackett, "British Policy and the H-Bomb", *The New Statesman and Nation*, August 21, 1954. See also *Manchester Guardian*, May 21, 1955.

[8] The Japanese Central Meteorological Observatory reported on May 27, 1956, a 'thermonuclear explosion somewhere in the Bikini area about as strong as the test on May 21'. [*The Times* (London), May 29, 1956].

[9] *The Times* (London), May 21, 1956. See also *Bulletin of the Atomic Scientists*, **12**, 230 (1956).

It may be mentioned here — and more about this is said in Chapter II — that most of the energy of the March 1954 thermonuclear explosion (as also of the other thermonuclear explosions so far conducted) was derived from *fission of uranium 238* ; the fusion (thermonuclear) process only served as a mechanism to produce fission in uranium 238. As will be seen later, the radiological hazard, for a given amount of energy released, is much greater for a fission process than for a fusion process.

The only other power, apart from the USA and the USSR, which has tested nuclear weapons is the UK. The UK had their first test of fission weapon in October 1952 at Monte-Bello Islands (Australia), and the second test a year later at Woomera Range in the South Australian desert. It is believed that the second test had some bearing on triggering-mechanism for thermonuclear weapons. The third test of fission weapons began in May 1956 at the Monte-Bello Islands. " This and the fourth test at Maralinga late this year are expected to supply experimental data for the triggering of Britain's first hydrogen weapon off Christmas Island in the Pacific in 1957 ".[10]

The important events in the ' nuclear-weapons-race ' are summarized in Table II.

US Release on March 1954 Explosion

On February 15, 1955, the US Atomic Energy Commission issued a report entitled *The Effects of High-yield Nuclear Explosions.* This was the first authoritative announcement regarding the far-reaching radiological hazard of the March 1954 explosion. On June 3, 1955, W.F. Libby (the chemist-member of the US Atomic Energy Commission) gave a valuable account of the effects of the radioactive fallout from thermonuclear explosions.

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[10] *The Times* (London), May 17, 1956.

TABLE II

(A-Bomb refers to atomic, *i.e. fission,* explosion. H-Bomb refers to *thermonuclear* explosion).

UK	USA	Year	USSR
	First pile made by Fermi	Dec 1942	
	A-Bomb (20 kiloton)	Aug 1945	
		Aug 1949	A-Bomb
A-Bomb Oct 1952	H-Bomb (5 megaton)	Nov 1952	
		Aug 1953	H-Bomb (1 megaton)
	H-Bomb (15 megaton)	March 1954	
		Nov 1955	H-Bomb : air burst (10 megaton)
	H-Bomb : air burst (15 megaton)	May 1956	

However, it is pertinent to observe in this connection that, were it not for the accidental exposure of the unfortunate Japanese fishermen to the radioactive fallout resulting from the US March 1954 test explosion, it is most likely that the world would have still remained in considerable, if not total, ignorance of the greatest hazard that confronts mankind. "On March 1, 1954 at 3-40 A. M., twenty three Japanese fishermen on board the fishing boat No. 5 *Fukuryu Maru* (Fortunate Dragon) were engaged in fishing in the Middle Pacific about 90 miles north-east of Bikini Atoll, when a reddish-white flash was seen on the horizon in a west-southwesterly direction, and seven or eight minutes later a loud explosion was heard. Afterwards it was learned that the flash and explosion had been caused by the hydrogen bomb test at Bikini Atoll. About three hours after the explosion, fine dust began to fall on the boat. The falling of dust lasted for several hours and ceased towards noon. The boat as well as the fishermen and the fishes caught by them were covered with a white sheet of fine dust. After a two weeks' voyage, on March 14, the No. 5 *Fukuryu Maru*, contaminated by radioactive dust, returned to Yaizu Harbor, Shizuoka Prefecture, Japan."—(From the special issue of the *Bulletin of the Institute for Chemical Research*, Kyoto University, November 1954, on the "Radioactive Dust from the Nuclear Detonation").[11]

Thomas E. Murray, one of the US Atomic Energy Commissioners, said in a speech[12] at the Golden Jubilee Dinner of the Fordham Law School on November 17, 1955: "I refer to the tragic incident of the Fortunate Dragon. This was the Japanese fishing vessel that was caught in the radioactive fallout from one of our thermonuclear tests at our Pacific Proving Ground in March 1954."

"Before these 1954 tests took place a policy of almost utter silence had been established. The decision was made to issue only two statements — first an announcement that tests were to be held, and then a short guarded statement at their conclusion. However, the inscrutable providence of God, our Father, decided otherwise. Radioactive dust settled on the Fortunate

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[11] The case of Aikichi Kuboyama, the radio operator of *Fukuryu Maru*, who died after an illness of about seven months, has been discussed by Y. Nishiwaki in *Atomic Scientists Journal*, **4**, 279 (1955). See also S. Sevitt, *Medical World*, **84**, 385 (1956). The likely cause of death was radiation from the radioactive fallout.

[12] Thomas E. Murray, *Vital Speeches*, **22**, 107, (1955); see also *New York Times*, Nov 18, 1955.

Dragon, some 90 miles downwind. You remember the results. The news about the potential hazard of radioactive fallout from thermonuclear weapons burst out of secrecy. Twenty-three Japanese fishermen announced to the world the first fateful news about the lurking catastrophe that may possibly lie in wait for all of us. In this instance, the official policy of secrecy proved inept. When the secret came out, through the wrong channels, the shock to world opinion rivalled in its own way the blast of the H-bomb itself."

USSR/USA Engineering and Scientific Manpower

There can hardly be any doubt that the most potent reason underlying the great Soviet technical achievements in nuclear weapons is the extreme stress laid by the USSR on technical and scientific education. As *The Times* (London) observed in its editorial of December 31, 1955: "Twenty years ago the Russians, through sheer ignorance, were still spoiling the machines they imported from abroad, but this year they were able to let off a hydrogen bomb. Behind the change lies an educational revolution which may be as significant for the world in the long run as the political revolution of 1917."

A detailed study of the professional man-power in the USSR has recently been published by DeWitt (National Science Foundation, USA, 1955). The present Russian output of University graduates in engineering exceeds the entire output of the rest of the world. In 1954 the Russian output of engineers was about 53,000 (30 percent of the total output of all graduates) as against 23,000 in the USA and 3,000 in the UK. Again the estimate of the total strength of engineers and scientists in the USA is taken to be a little over 800,000 whereas for the USSR the figure is about two-and-a-half times larger.

The US Atomic Energy Commission estimates that the demand by 1965 for scientists and engineers engaged in the peaceful uses of atomic energy in the USA would be, on a conservative basis, of the order of 50,000. This is far in excess of what is likely to be achieved according to the present educational and training programmes.[13] As Libby has observed, the ultimate limiting factor in the advancement of peaceful uses of atomic energy in the USA is the " acute shortage of trained manpower ".

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[13] *Nucleonics*, **14**, 21 (1956).

CHAPTER II

FISSION AND FUSION EXPLOSIONS

This chapter is mainly concerned with the broad scientific principles underlying fission and fusion explosions. The principle of the fission-fusion-fission explosion (*e.g.*, March 1, 1954, Bikini test explosion) is described in the last part of this chapter.

It is now common knowledge that all matter consists of molecules and atoms, and all atoms consist of a central core, called the *nucleus*, around which revolve electrons. All nuclei are built from two fundamental particles — protons and neutrons. The neutron is electrically neutral. The proton has a positive charge equal and opposite to the charge of the electron. (A neutron is slightly — one part in 750 — heavier than a proton which has 1836 times the mass of an electron. A neutron, outside a nucleus, is an unstable particle: It has a half-life of about quarter of an hour and decays into a proton and an electron).

Nuclei of large mass numbers, *e.g.*, uranium and thorium, release energy in fission, *i.e.*, on breakdown into nuclei of medium mass numbers. Nuclei of small mass numbers, generally speaking, give out energy on fusion, *i.e.*, synthesis into bigger nuclei. The best example of this fusion process is the formation of helium from hydrogen.

The mass number (A) of a nucleus is the number of neutrons and protons contained in it. The number of protons defines the atomic number (Z) of the nucleus. The atomic number is characteristic of an element; for example, it is 1 for hydrogen, 38 for strontium and 92 for uranium. For the same element there can exist nuclei having different values of the mass numer (A). They are called isotopes of the given element. A nuclear species (nuclide) is specified by assigning values for Z and A. Thus, $Z = 92$, $A = 235$, defines an isotope of uranium with mass number 235, generally written as uranium 235. Uranium 238 contains 92 protons and 146 neutrons, making a total of 238 nucleons — a nucleon stands for either a proton or a neutron. The protons and neutrons are most strongly bound in nuclei of moderate mass numbers, and the binding is relatively weak in heavy as well as light nuclei. It is on this account that heavy nuclei liberate energy on fission and light nuclei on fusion.

Uranium, as it occurs in nature, is a mixture of 0·006 percent of uranium 234, 0·712 percent of uranium 235 and 99·282 percent of uranium 238. Uranium 235 is obtained from natural uranium by separating uranium 235 from the far more abundant uranium 238 by the process of thermal diffusion. Plutonium 239 is produced in nuclear reactors. *Uranium 233 is made from thorium* in special types of reactors. The production of these substances is a tedious, elaborate and expensive process, and the cost is of the order of $ 10,000 per lb. The cost of natural uranium (refined metal) is less than $ 40 per lb. (The cost of heavy water is about $ 25 per lb).

Self-sustained and Externally-maintained Fissions

In a few substances which we shall often refer to as fissile substances and of which the most important are uranium 235, uranium 233 and plutonium 239, a fission process when once initiated, under suitable conditions, propagates itself through the mechanism of a self-sustaining chain reaction. Further, under specialized conditions such a chain reaction can be maintained in mixtures of fissile and non-fissile materials, even when the proportion of fissile material is relatively small.

In substances like uranium 238 and thorium 232, fission when once started is not self-sustained. It can only be maintained by a continuous injection of high energy neutrons. (More about this is said in Appendix I). It is important for our purpose to distinguish between the two types of fission described above. We shall call the fission process of the first type as *self-sustained fission* or merely fission for brevity. The second will be called *externally-maintained fission* or E-fission.

In the case of natural uranium a self-sustained chain reaction is not possible unless it is mixed with a ‘ moderator ’ as is done in a nuclear reactor or pile. Such an arrangement generates energy at too slow a rate to be of any effective use as a bomb. Thus for the purpose of a bomb it is only the E-fission which is relevant for *natural* uranium. (A reactor accidentally getting out of control may lead to an explosion but because of the time period involved in this case, the explosion would be extremely weak, in comparison with an atomic bomb).

Fusion Process

A fusion reaction can be realized in a variety of ways, *e.g.*, by bombarding light elements with charged particles obtained from cyclotron and other high-energy particle-accelerators.[1] However, in these cases, it is important to observe that only an extremely small fraction of the bombarding particles is utilized for fusion and hence the energy obtained is extremely small compared to the energy required for accelerating the bombarding particles. On the other hand, we are here concerned with processes in which the energy output is substantially more (in practice should be very much more) than the energy input required for the realization of the process. Such a process becomes possible only at exceedingly high temperatures of the order of millions of degrees. It is only at such high temperatures that there will exist nuclei — these will be an extremely small fraction of all nuclei present — which would have kinetic energy of thermal motion large enough to overcome the electrical repulsion between them and permit their coming sufficiently close together to make fusion possible. This fusion process is called thermonuclear process or reaction. The rate of thermonuclear reaction is extremely sensitive to temperature. For all practical purposes hydrogen and/or its isotopes, deuterium and tritium, are essential ingredients in thermonuclear reactions.[2]

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[1] A fusion reaction, but not thermonuclear in origin, has been realized by Soviet scientists by passing currents of the order of a few hundred amperes through heavy hydrogen. In a lecture delivered at Harwell on April 25, 1956, I.V. Kurchatov "has been the first to speak frankly, and from the inside, on any aspect of the subject. There may be other aspects on which he did not touch. But for the purpose of future discussion of fusion reactions, his lecture may come to seem as much a beginning as, on an international scale, was the first proposal for holding of the Geneva Atomic Conference for the discussion of what, now, is conventional atomic energy". (*The Times* (London), *Science Review* No. 20, Summer 1956).

Nomenclature for Nuclear Explosions

It is necessary in dealing with nuclear explosions to adopt some definite nomenclature, if confusion is to be avoided. A *nuclear explosion* (or weapon) is an explosion (or weapon) in which all or most of the energy is derived from a nuclear process, either fission or fusion, or a combination of both.

Let us first consider a fission explosion. If the fission process is of the self-sustained type, the explosion will be called a *self-sustained fission explosion* or fission explosion for brevity. In deference to current terminology we shall speak of it as an *atomic explosion* or *A-explosion* (A-bomb). A 20 kiloton TNT equivalent weapon is called a *nominal atomic bomb.* When the fission process is of the externally-maintained type (as in uranium 238), the explosion will be called an *externally-maintained fission explosion.* It will be seen later that the energy released in an externally-maintained fission explosion is (usually) of the order of millions of tons of TNT and with a correspondingly large production of radioactive fission products. The US Atomic Energy Commission had described such explosions as *high-yield* explosions as distinguished from *low-yield* explosions (in the range of kilotons of TNT) which are of the self-sustained fission type.

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[2] This is due to the fact that hydrogen nuclei have the smallest electrical charge and hence the effect of coulomb repulsion is least for this case.

In current literature there has been considerable confusion about the use of words thermonuclear explosion, fission explosion and fusion explosion (H-bomb). In the absence of official announcement it was at one time believed that the explosion energy of the megatons test explosions was practically all derived from thermonuclear reactions and as such they were called thermonuclear or fusion explosions. Now that it has become clear — and this is more fully described later — that this was not so, at any rate for the megatons explosions conducted in 1954, it would obviously be misleading still to refer to them as fusion or thermonuclear explosions. In these megatons explosions the thermonuclear reactions served as a triggering mechanism only. It is obviously preferable to name an explosion by the process which is mostly responsible for the energy released in it rather than call it by its triggering mechanism or any other ancillary device. We shall therefore, as far as possible, avoid the old terminology and refer, for example, to the March 1954 explosion, as high-yield fission explosion or simply high-yield explosion.* A 20 megaton TNT equivalent weapon is called a *nominal high-yield weapon.*

We shall call as a fusion explosion one in which the energy is almost entirely due to a fusion process (thermonuclear reaction) and, to emphasize this fact, we shall sometimes speak of it as an *all-fusion* explosion. The different types of explosion are shown below:

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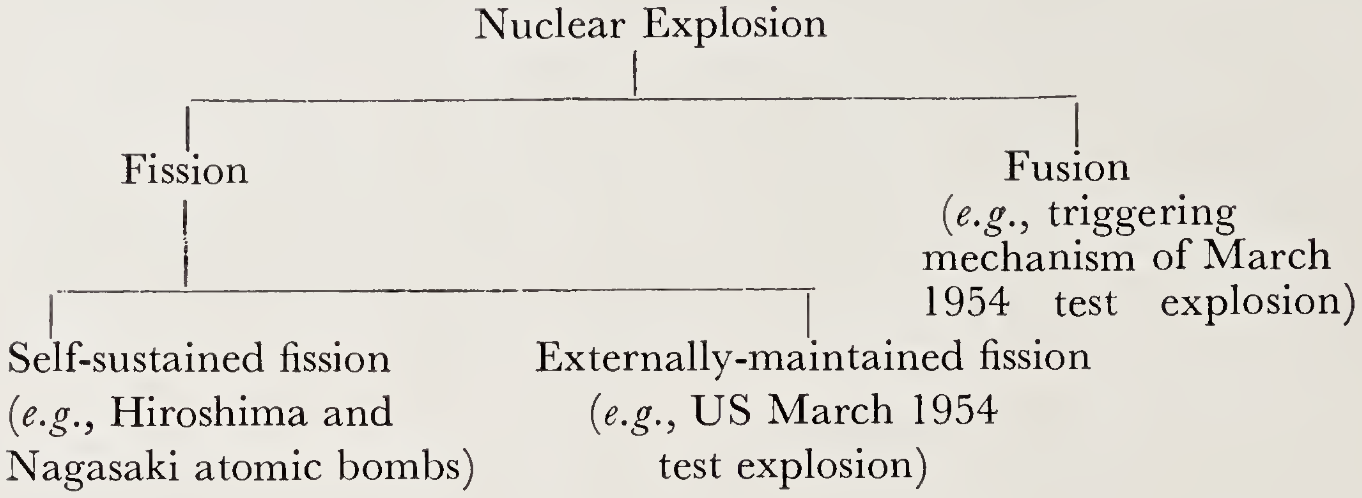
* For convenience of exposition the 'old terminology' has been used in Chapter I.


Nuclear Explosion
Fission
Fusion
(*e.g.*, triggering mechanism of March 1954 test explosion)
Self-sustained fission
(*e.g.*, Hiroshima and Nagasaki atomic bombs)
Externally-maintained fission
(*e.g.*, US March 1954 test explosion)

March 1954 Bikini Test Explosion

After this digression on terminology, we come now to the historic March 1954 test explosion. This released energy equivalent to millions of tons of TNT, generally estimated at about 15 million tons.* This is the only test explosion about which some information has been officially released. The US Atomic Energy Commission for the first time in their report of February 15, 1955 described in broad outlines the pattern of radioactive local fallout of the ‘ thermonuclear device ’ (the AEC called it so in their report) detonated at the Bikini Coral Island on March 1, 1954. It was apparent, though the report said nothing about it, that the area of radioactive contamination due to the fallout was very much larger than could possibly arise from an all-fusion explosion of energy equivalent to some millions of tons of TNT. J. Rotblat[3] was the first to make the definite suggestion that the only way one could possibly account for the large fallout (reported by the AEC) was to assume that what the AEC called a 'thermonuclear device' was essentially a *fission device.* He also suggested, as the next obvious step, that the abundantly available uranium 238 had been used for this purpose. Suggestions to the same effect also came from R.E. Lapp[4]. Though no official release has as yet been made by the AEC, the June 3, 1955, statement of W.F. Libby[5] (member of the AEC) leaves hardly any doubt that most of the explosion energy came from fission. J. Cockroft[6] also stated the same thing in his address (April 1955) to the UK Parliamentary and Scientific Committee. He said that the explosion produced hundred to thousand times more radioactive products than an atomic bomb, and continued: "The contamination, however, is of the same kind. The same radioactive fission products are produced and their activity decays in the same way."

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* See for instance *Nuclear Weapons*, (Manual of Civil Defence: Vol. I, Pamphlet No. 1), H.M.S.O., 1956.

[3] J. Rotblat, *Atomic Scientists Journal*, **4**, 224 (1955).

As remarked earlier, the radiological hazard imposed by an all-fusion explosion is relatively insignificant (say, one-hundredth) compared to that of a fission explosion of the same energy. One could, by incorporating in the all-fusion bomb some suitable substance (*e.g.*, *cobalt*) which would become strongly radioactive on absorption of neutrons liberated in the explosion, increase the radiological effect, but it would still be much below that of a fission bomb of the same energy. "The cobalt bomb would offer no advantages to a lunatic designer." Incorporation of cobalt in a fission bomb would not make any material difference to its radiological hazard.

Valuable evidence — and this came earlier than Rotblat's suggestion — also came from the work of the Japanese scientists who analyzed the radioactive ash that fell on the decks of the 'Fortunate Dragon'.

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[4] R.E. Lapp, *Bulletin of the Atomic Scientists*, **11**, 45, 206 (1955).

[5] W.F. Libby, *Bulletin of the Atomic Scientists*, **11**, 256 (1955).

[6] J. Cockroft, *Nature*, **175**, 873 (1955).

They[7] identified in the ash considerable activity due to the uranium isotope U237. This isotope undergoes beta-decay with a half-life of only about a week, and because of this short life it does not occur in natural uranium. It is produced when uranium 238 absorbs one fast neutron (energy about 10 mev) and emits two neutrons instead, thus losing in the balance one neutron. Again, as such high-energy neutrons have a negligible chance of being produced in a fission process, but on the other hand are copiously produced in the $(H^3 - H^2)$ fusion reaction, their presence (inferred from the presence of uranium 237) is very interesting evidence indicating the use of a thermonuclear reaction as triggering mechanism in the Bikini explosion[8].

Mention should also be made here of the discovery[9] of two new elements, einsteinium ($Z=99$) named after Einstein and fermium ($Z=100$) named after Fermi, in the thermonuclear test (Mike) of November 1, 1952 at Marshall Islands: The nuclides

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[7] See for instance Y. Nishiwaki, *Atomic Scientists Journal*, **4**, 279 (1955). Japanese observers also recorded U237 in the fallout from the USSR thermonuclear explosion of Nov 1955. [*Time*, April 16, 1956].

[8] We may also recall that unusually high radioactivity was found in rain which fell in the southern and central parts and along the Pacific coast of Japan from middle to end of May 1954. It decreased later, but there was a sudden rise again after the middle of September, mostly in the southern part of Japan. The radioactivity during May was of the order of 0.1 — 1.0 microcurie per liter, which is a few thousand times more than the maximum permissible radioactivity in drinking water. The radioactivity in May was of course due to the March explosion, but the origin for the September rise was not clear. It may possibly have been due to some Soviet test explosions in north-eastern Siberia or Wrangel Islands. Radioactivity was also detected in the rain over Calcutta on April 29 and subsequent days till about the middle of July 1955. The dust and oil samples collected from aeroplanes were also found to be radioactive, the activity decaying according to the usual decay law. [Y. Nishiwaki, *Atomic Scientists Journal*, **4**, 279 (1955); also S. Chatterjee, *ibid.*, p. 273].

[9] A. Ghiorso *et al.*, *Physical Review*, **99**, 1048 (1955). See also P.R. Fields *et al.*, *Physical Review* **102,** 180 (1956).

(99^{253}, 99^{255}, 100^{255}) were found in the irradiated uranium (U238) residue of the explosion. They arise from absorption of neutrons by U238, and as an U238 nucleus has to absorb as many as 17 neutrons to form E^{255} or Fm^{255}, it gives some indication of the terrific neutron flux in the 'Mike' test explosion.

One may ask that if the March 1954 megaton test was a fission explosion then why one had to wait a decade after Hiroshima to achieve it. The energy of this explosion was a thousand times more than that of the Hiroshima bomb, but this could have been obtained by taking a thousand times larger amount of uranium 235 than what was used in the 1945 bomb. What was new about it ? The answer is quite simple. It rests on weapon economics which is a dominant, and indeed a supreme, consideration in military planning. This is not the place to go into the economics of weapon systems. A weapon system is a complex of war-head, means of delivery and numerous other relevant factors. It is enough to say that the efficiency of a weapon system is determined by the ratio — and except in very simple cases it is extremely difficult to assess this ratio in quantitative terms — of the damage inflicted on a target complex, and the effort and resources going into the production of the weapon system under consideration. As an illustration, imagine a target complex that requires a concentration of an explosive energy equivalent to say 20 million tons of TNT. If this much energy is obtained from TNT the cost would be of the order of 10 billion dollars or about one-third the US Armed Forces budget ; and if it is obtained from a fissile material (assuming that 20 percent of the material actually undergoes fission during the explosion) the amount required would be about 5,000 kilograms at a cost of about 100 million dollars[10]. However, if one could use natural uranium instead of a fissile material, the cost would be about quarter million dollars. It is, of course, absurd to ignore tne means of delivery in comparing the relative effectiveness of conventional high explosive bombs with nuclear weapons, but ignoring this factor only serves to emphasize the extraordinary ‘ cheapness ’ of nuclear weapons as compared to conventional weapons. The mere factor of bulk would make the means of delivery of nuclear weapons far more economical than conventional weapons for the same target effect. In spite of the crudeness of the foregoing argument, it should be evident why countries whose dominating aim is to stock-pile explosive energy and which have the requisite scientific and industrial resources, go in for nuclear weapons instead of weapons based on conventional explosives. For the same money and effort nuclear weapons, in comparison to conventtional weapons, give thousands of times (if not more) larger yield in terms of target-damage.

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[10] The total output of uranium 235 and plutonium 239 is believed to be about 20,000 kilograms a year.

It, therefore, marked a decisive advance when it was realized that in a megatons explosion one could employ uranium 238 as the source of most of the energy. If one could use uranium 238, one could also use natural uranium, but it is more economical to use uranium 238 which is the residue left (waste product) after most of the very expensive uranium 235 has been extracted from it in the thermal diffusion plants and nuclear reactors. Thorium also could possibly be used, and maybe, has already been used.

The fission of uranium 238, however, requires neutrons of much larger energy than on an average, become available in the fission process, and hence the fission, even when once started, cannot be self-sustained through a chain mechanism. It can only be maintained by continually injecting high-energy neutrons (of energy comparable to, say, 5 million-electron-volts).* These energetic neutrons are supplied by a thermonuclear process. The thermonuclear process requires extremely high temperatures for its initiation and would thus require a suitable triggering device. It would be of some interest to say at this stage a few words as to how this triggering can be done.

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*1 million-electron-volt (mev) represents the energy of an electron falling through a potential difference of 1 million volts. It is equal to 1.6×10^{-6} erg.

A thermonuclear reaction is extremely sensitive to temperature. Take, for instance, the tritium and deuterium reaction, which in comparison to all other nuclear reactions acquires an appreciable rate even for a temperature of a million degrees. However, if the temperature be raised from about one million to two million degrees, the rate of reaction would be multiplied about a million-fold. At a temperature of two million degrees — the reaction rate is insensitive to density variations — the rate of energy generation is of the order of ten thousand million calories per second per gram of the mixture.[11]

When the process is once started, it can be maintained, and even accelerated by its own heat production, so long as the conditions are such (*e.g.*, the reacting mass is sufficiently large) that the rate of loss of heat from the reacting system to the outside is less than the rate at which heat is produced by the fusion process. When this condition is no longer satisfied, the temperature drops and the reaction soon ceases.

The most likely mechanism for providing these high initiating temperatures is a self-sustained fission explosion. It appears possible, and maybe the possibility has been actually realized, that the triggering can be done with ordinary chemical explosives, either using the shaped-charge[12] principle or the phenomenon of shock-waves. Velocities as high as 10^7 cm/sec have been recorded for a very small front portion of Munroejet obtained from beryllium liner fired in vacuum[13]. This large kinetic energy would correspond to a temperature comparable to a million degrees. The average velocity for Munroe-jets is, however, about ten times less.

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[11] L.N. Ridenour, *Scientific American*, **182**, 11 (1950).

[12] For recent work on shaped-charges, see for instance, Sampooran Singh, *Defence Science Journal*, **5**, 169 (1955).

We now come to uranium 238 fission explosion. It is thus essentially a three-stage process: fission-fusion-fission. Let us consider a 20 megaton bomb, as an illustration. The first stage is fission of a fissile material (say plutonium) producing about half-a-megaton energy. This energy corresponds to an actual fission of 25 kilograms of the fissile material; the total amount of the material would be about 5 to 10 times larger, depending on the efficiency of utilization. Most of the neutrons released in this fission process have insufficient energy to cause fission in uranium 238. The main function of the fusion reaction, therefore, is to provide the required high-energy neutrons. The fission process of stage I provides the extremely high temperature necessary for the fusion reaction to take place. The fusion mixture and the fissile material could form an integral assembly and the detonation of the fissile mass be set off by imploding it using ordinary high explosive for the purpose. (The implosion principle is explained in Appendix I). An energy corresponding to 20 million tons of TNT necessitates fission of very nearly 1,000 kilograms of uranium 238. It would require something like 20 kilograms of the fusion mixture lithium 6 deuteride (Li^6D) to generate the required number of high-energy neutrons. The fusion mixture may also possibly contain a very small amount of tritium to start the thermonuclear reaction. The fusion mixture itself would liberate energy equivalent to 2 megatons of TNT. The neutrons of stage I react with lithium 6 to produce tritium which in its turn reacts with deuterium, producing neutrons of very high energy.

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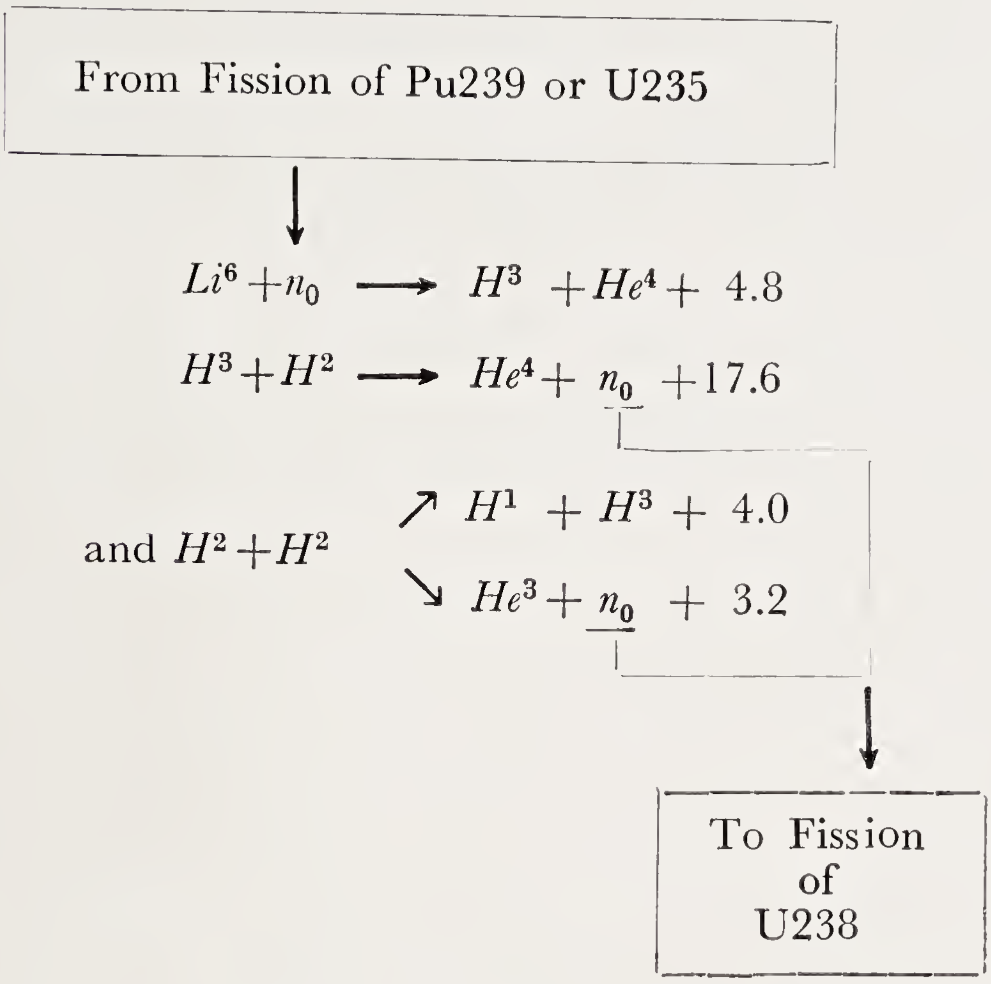
[13] W.S. Kosky, *et al.*, *Journal of Applied Physics*, **23**, 1300 (1952). See also H.V. Hajek, *Explosivstoffe*, **3**, 65 (1955).

The probable *fusion* reactions are noted below (energy is in mev units) :


From Fission of Pu239 or U235
$Li^6 + n_0 \longrightarrow H^3 + He^4 + 4.8$
$H^3 + H^2 \longrightarrow He^4 + n_0 + 17.6$
and $H^2 + H^2$
$\nearrow H^1 + H^3 + 4.0$
$\searrow He^3 + n_0 + 3.2$
To Fission of U238

We have thus seen that the energy of the fission-fusion-fission bomb is practically all due to the fission of uranium 238 : It is probably responsible for more than 80 percent of the total energy. The ‘ progress ’ in nuclear weapons during the last decade may be summed up as: *From Uranium 235 to Uranium 238.* That in a nutshell expresses the progress in nuclear weapons since Hiroshima.

It has been said earlier that for the same explosion energy the radioactive hazard of an all-fusion explosion is far less as compared with that of a fission explosion. Under certain tactical situations (*e.g.*, demolition of areas, air-strips etc., which later may have to be occupied and used) an all-fusion bomb would offer an advantage over a fission bomb. The development of an all-fusion bomb is likely to be more difficult than that of a fission-fusion–fission bomb, one possible reason being that in the case of the latter the fusion core is surrounded by a large mass of uranium 238 which itself attains very high temperatures on account of the fission it suffers (under bombardment of neutrons from the fusion core). As such, the loss of heat to the outside from the fusion core would be much less than in the absence of the uranium envelope. It seems that attempts are being made to develop a fusion bomb. For instance, it has been mentioned in some unofficial press reports that the USA test of May 21, 1956, was an all-fusion bomb of the megatons class. Possibly a substantially smaller bomb of the same type was tested on May 5, 1956. However, on general principles it seems unlikely that an all-fusion bomb could be made which will have an energy appreciably less than a million tons of TNT.

APPENDIX I

FISSION EXPLOSION AND CRITICAL SIZE: IMPLOSION

In this appendix we give a brief (almost naive) account of the fission-chain process, the concept of *critical size* and the principle of *implosion* as applied to atomic explosions[1].

A uranium 235 nucleus, on capturing a neutron, undergoes fission. It splits into two approximately equal daughter nuclei (fission into three fragments has been observed, but this is an extremely rare event) and two to three neutrons (the average is 2·5). These neutrons are emitted within about 10^{-15} second of the act of fission. These are called *prompt neutrons.* Neutrons are also emitted by the fission products for an appreciable time—fraction of a second to several seconds—after the fission act: These are called *delayed neutrons*, their number being no more than one percent of prompt neutrons. The energy of most of the prompt neutrons lies between one and two million-electron-volts (mev). The energy spectrum from about 0·1 to 18 mev is given by:

$$n(E) = \sqrt{\frac{2}{\pi e}}\; e^{-E} \sinh\sqrt{2E} \qquad (E \text{ in mev})$$

where n(E) is normalized to unity. A maximum in the curve occurs at about 0·8 mev, and for E greater than 2 mev the curve drops off exponentially. (The above spectrum refers to fission caused by slow neutrons in U235 or Pu239, but roughly the same sort of relation is expected to hold for fission due to fast neutrons).

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[1] For a detailed account of the fission process reference may be made to *Reactor Handbook*: *Physics*, USAEC (1955).

In the case of U233, U235 and Pu239, there is no lower limit for the kinetic energy that a neutron must possess to enable it to cause fission on capture by a nucleus. For this reason, these are called *fissile materials*, and only these three are of practical significance. In the case of a non-fissile nucleus, the energy of the incident neutron must exceed a certain threshold value to enable it to cause fission on capture: For U238 and Th232 the threshold value is very nearly 1.1 mev. (Speaking generally, any heavy nucleus can undergo fission if the excitation energy is great enough, *e.g.*, fission in gold occurs for neutron energy of about 100 mev).

Consider a mass of pure U235. A capture of a neutron by an U235 nucleus results in fission, thus producing more neutrons which again on capture by U235 nuclei produce still more neutrons. Thus the chain reaction continues and the neutron population multiplies, until depletion of uranium and production of neutron-absorbing products or other circumstances puts a stop to the chain process. The above self-sustained chain process is spoken of as a fast neutron process because the average energy of the neutrons participating in the chain reaction is high—of the order of a million-electron-volts. Things are quite different, if we have a mass of pure U238 or natural uranium. In this case, even when a neutron has an energy above the threshold value for fission, the most likely result of its collision with a U238 nucleus would not be a capture but inelastic scattering, the neutron energy thus falling below the threshold value so far as the subsequent collisions are concerned. The overall effect of all this is that a neutron-capture resulting in fission is a very occasional event. Most of the captures are fissionless with a consequent subtraction of neutrons from any neutron corporation. When the matter is examined quantitatively in terms of the observed cross sections for fission, radiative capture (capture of neutron with emission of a gamma ray), elastic and inelastic scattering and other possible processes, it is found that a self-sustained chain reaction in pure U238 or pure Th232 or natural uranium is not possible. This fact is important in connection with fission-fusion-fission explosions described in Chapter II. Tables III and IV would be of some interest in this connection.

A chain reaction can, however, be sustained in natural uranium if we can somehow cut down to negligible limits the deleterious effect of U238 nuclei. The way it is done in a nuclear reactor is to arrange things such that neutrons produced in fission (of U235 present in natural uranium) can almost immediately escape from the uranium mass (which is usually in the form of a lattice

TABLE III

Fission and total cross section for different neutron energies[2]

(Unit is barn $=10^{-24}$ cm^2)

σ_f = fission cross section,

σ_t = total cross section (including scattering).

	σ_f			σ_t		
Neutron energy	Thermal (velocity =2200 m/s) =0.025 ev	1 mev	2 mev	0.025 ev	1 mev	2 mev
Uranium 235	600	1	1	700	7	7
Uranium 238	0	0.02	0.5	11	7	7

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[2] *Neutron Cross Sections*, USAEC (1955).

of uranium rods[3]) into a ' moderator ' and after spending a little time there go back into uranium. The function of a moderator (graphite, heavy water, beryllium or ordinary water) is to slow down neutrons from their initial energy of a million-electron-volt or

TABLE IV

Values[4] of ν and η

ν =average number of neutrons emitted per fission, and η = average number of neutrons emitted per neutron absorbed.

	Average number (ν) of neutrons emitted per thermal neutron absorbed in fission	Average number (η) of neutrons emitted per thermal/fast neutron absorbed	
		Thermal	Fast
Uranium 235	2·46	2·08	2·33
Uranium 233	2.59	2·29	
Plutonium 239	2·95	2·08	2·7

When η is less than unity, a self-sustained chain reaction is not possible. For natural uranium η is 1.32 for thermal neutrons (energy of thermal neutrons is fraction of an electron-volt) and $\eta < 1$ for fast neutrons. In pure uranium 235 about 84 percent of thermal neutron-captures cause fission ; the figure is 65 percent for plutonium 239.

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[3] It has been shown that a homogeneous mixture of natural uranium and graphite, no matter how large such a mass may be, would not sustain a chain-reaction. A homogeneous mixture of heavy water and uranium (heavy water is a better moderator than graphite) could go *critical,* if the mass were sufficiently large.

[4] *Reactor Handbook*: *Physics,* USAEC (1955) : See also W.H. Zinn, 'Review of Fast Power Reactors', *Proceedings of the International Conference on the Peaceful uses of Atomic Energy held at Geneva, 1955,* Vol. 3, (United Nations, 1956).

so, to a small fraction of an electron-volt (thermal energies) without absorbing any appreciable fraction of them by radiative capture. The probability of capture of a thermal neutron by U235 is hundreds of times larger than for U238. In other words, though U238 is present in much greater abundance than U235, the *thermal neutrons* do not ‘ recognize ’ its presence.

However, this beautiful ‘ trick ’ is of no avail in the case of fission weapons, for here the fission energy must be released in a time of the order of a *microsecond.* In this case there is not enough time to slow down the neutrons, and hence for a fission explosion one has to use a pure fissile material or, at any rate, material containing a very high percentage of it. For the same reason it is only the *prompt* neutrons that are relevant to this case. The *delayed neutrons* play no role in a fission explosion, though their role in reactor-control is most vital: They make a reactor the practical thing it has proved to be.

It is obvious from what has already been said that a sufficiently large mass of a pure fissile material is necessarily unstable: It would explode spontaneously, the fission-chain set off by any stray neutron or neutrons produced in ‘ spontaneous fission ’.[5] As each neutron-capture gives rise to more than two neutrons, the chain builds up at a terrific rate. If we assume for an order-of-magnitude argument a capture cross section of a barn (10^{-24} cm^2), it immediately follows that a fissile mass as big as a thousand kilograms would be fissioned in a time of the order of a few microseconds. The next question is: What happens if the fissile mass is very small ?

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[5] Spontaneous fission of uranium was discovered in 1940 by the Russian scientists G. N. Flerov and K. A. Petrazhak. The rate of disintegration is about 1 per hour per gram of uranium 235. The half-life for spontaneous fission, as found experimentally, depends exponentially on Z^2/A. It is 10^{19} years for $Z^2/A=35$ and 10^{-20} second for $Z^2/A=45$. The element mendelevium ($Z=101$; $A=256$; $Z^2/A=39.8$) has a half-life of the order of an hour or so.

Let us consider a mass which is so small that a neutron placed well within it has a high probability of reaching the surface (boundary of the mass) and escape to the outside without suffering a collision with a nucleus. In such a situation most of the fission neutrons would be lost to the outside instead of participating in a chain process, which, therefore, would not be sustained. This leads to the important concept of *critical size* or *critical mass*.[6] The continuation of a chain reaction requires that, on an average, for every neutron lost either by absorption in the system or escape to the outside, at least one fresh neutron is added by fission to the system. A system for which the above condition is just satisfied is called *critical*. For an over-critical (or super-critical) system, the number of neutrons added for every neutron lost is more than one; and the chain process builds up at a terrific rate. For a sub-critical system more neutrons are lost than added, and the chain reaction cannot be sustained. It is apparent on a little reflection that the linear dimension of the *critical mass* must be comparable to the mean-free-path of the fission neutron. The linear dimension with which we are concerned here is, of course, the effective linear dimension, *e.g.*, diameter in the case of a large spherical mass or thickness of the wall in the case of a thin spherical shell. It should, therefore, be possible to arrange things in such a way that a given amount of fissile material, when sub-critical in the form of a thin spherical shell, becomes critical when compressed into a solid sphere. This compression can be brought

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[6] If we take for the radius of a critical sphere the expression (following an order-of-magnitude theory of fast-reactors) :

$$R \sim \frac{\pi A}{d N_0 \, (3\sigma_t \, \nu \sigma_f)^{\frac{1}{2}}} - \frac{0.71 A}{\sigma_t \, d N_0},$$

we have, on substituting numerical values from Tables III and IV, for R the value 7.3 cm. This gives for the critical mass the value 30 kg. (In the above expression d denotes the density and A the mass number of uranium. N_0 is Avogadro's number).

about by firing of a suitable chemical explosive placed on the outside of the hollow sphere. Once the system becomes over-critical, the chain-reaction starts and results in the detonation of the fissile material. This is called the *implosion principle.* It is believed that it was first used in a crude form in the Nagasaki bomb. (The principle of detonation of the Hiroshima bomb is supposed to be somewhat different. It consisted in bringing together separate sub-critical masses so that the combined mass exceeded the critical size. The masses enclosed in something like a gun-barrel were impelled against each other under the action of chemical explosives).

It has been mentioned that for a critical configuration the effective linear dimension has to be comparable to the mean-free-path of the neutron. The latter is inversely proportional to the number of nuclei per unit volume and hence, roughly speaking, the critical mass should be inversely proportional to the square of the density of the fissile material. If a mass which is initially just critical suffers an expansion — which it must on account of the rising temperature and pressure produced by the fission process itself — the density falls, and the mass becomes sub-critical and the chain reaction stops as a consequence of it. The chain process would also be retarded by fission products produced in the reaction, many of which strongly absorb neutrons. On both these counts, it is necessary for a nuclear detonation that one must start *initially* with a mass very much larger than the critical mass. Even in the ideal case the chain process must stop when the unfissioned mass is below the critical value. Thus, in every atomic weapon, an amount of fissile material at least equal to the critical mass must inevitably be wasted. From this it should be obvious why smaller atomic weapons make a much less economical use of the fissile material than larger ones.

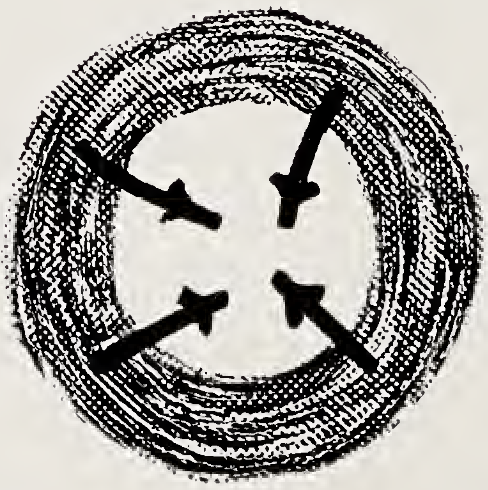
The dependence of the critical mass on the density can also be used to one's advantage. Let us consider that during the fission process — at any rate during its early stages—the fissile material is subjected to an intense pressure of the order of a million atmospheres or so. The fissile material would be compressed to a density, say, twice the density of the normal metal, and the critical mass thus reduced to one-fourth of its original value. The high pressure is produced (it is believed) by a refinement and development of the *implosion technique.* A weapon utilizing this principle is called a 'sub-critical weapon'. In sub-critical weapons the fissile material is used to a much greater advantage than would otherwise be the case. It is in this way, it seems, that efficiencies of 20 percent (percentage of fissile material that suffers fission) and possibly more have been realized.

It should again be mentioned that the successful achievement of a nuclear explosion depends on the fact that the build-up of a fast-neutron-chain process is extremely rapid. Were it not for this extremely rapid build-up, the bomb casing which is subjected to exceedingly large accelerations — say, of the order of 10^{12} cm/sec^2 — would undergo during the course of the fission-process itself considerable expansion, thus reducing the density of the fissile material inside it. This, if carried far enough, would stop the chain reaction for reasons explained above. For the high pressures one encounters in nuclear explosions the tamping or retaining property of the bomb casing depends only on its mass, *i.e.*, inertia, the strength of the material having negligible effect.

The study, experimental and theoretical, of critical systems of pure fissile materials has now acquired added importance because of the valuable information it provides not only for weapons design but also in the design of fast reactors, *i.e.*, reactors in which the chain process is sustained by fast neutrons. Such reactors have no moderators; they are comparatively small in size; and are being investigated for *breeding* (*i.e.*, producing more fissile material than what is consumed in the process) fissile materials from fertile materials *e. g.*, U233 from thorium 232. A fertile material is one which can be transformed into a fissile material. An example of a fast reactor is the US reactor EBR which was set up in December 1951. Another example is the UK Dounreay reactor under construction at a cost of some millions of pounds. (The fission products in the core would have radioactivity of a hundred million curies.)

A brief description of three simple experimental critical systems is given in *Nucleonics* (October 1955). They are named *Godiva* (U235), *Topsy* (U235) and *Jezebel* (Pu239). They have also been used as powerful instantaneous sources of neutrons (50 microsecond pulse of 10^{16} neutrons) in studies of *delayed neutrons* emitted from fission of irradiated materials. The experimental system, to start with, is sub-critical, and hence safe. Its parts are brought closer together (by remote control) so that the system becomes slightly above *delayed critical*, *i.e.*, critical with respect to the total number of neutrons—prompt and delayed. For such an assembly the build-up of the chain process is comparatively very slow as it depends on the delayed neutrons. When the system (*Godiva*) is delayed critical, then " a U235 slug is shot into the assembly and stopped near its most effective location. When the system is a bit above prompt critical, the fission rate rises extremely rapidly, the uranium heats, expands, thus dropping the reactivity enough to terminate the fission burst. Thus, a potentially run-away burst is stopped by thermal expansion. With a typical *Godiva* burst the initial rise in fission rate is exponential with a period of about 15 microseconds and continues to a maximum power level of nearly 10^9 watts, then falls off in a manner similar to the build-up ".

Notice that we have here a striking illustration of a critical assembly becoming sub-critical because of expansion and consequent reduction in density of its fissile mass.



APPENDIX II

NUCLEAR REACTIONS OF LIGHT NUCLEI

The important fusion reactions are enumerated below. The energy (Q) released in a reaction is given in million-electron-volts (mev).

Reaction	Q
$H^1+H^1 \longrightarrow H^2+\beta^{+}+\nu_0$	0.42
$H^1+H^2 \longrightarrow He^3+\gamma$	5.5
$H^1+n_0 \longrightarrow H^2+\gamma$	2.26
$H^2+H^2 \longrightarrow He^3+n_0$	3.25
$H^2+H^2 \longrightarrow H^1+H^3$	4.0
$H^3+H^1 \longrightarrow He^4+\gamma$	19.7
$H^3+H^2 \longrightarrow He^4+n_0$	17.6
$H^3+H^3 \longrightarrow He^4+n_0+n_0$	11.3
$Li^6+n_0 \longrightarrow H^3+He^4$	4.8
$Li^6+H^1 \longrightarrow He^3+He^4$	4.0
$Li^6+H^2 \longrightarrow He^4+He^4$	22.4
$Li^7+H^1 \longrightarrow He^4+He^4$	17.3
$Li^7+H^1 \longrightarrow Be^8+\gamma$	17.2
$Li^7+H^2 \longrightarrow He^4+He^5$	14.2
$Li^7+H^2 \longrightarrow Be^8+n_0$	15.0

ν_0=neutrino; β^{+}=positron; β^{-}=electron; n_0=neutron; H^1=hydrogen; H^2=deuterium; H^3=tritium; He^3=helium nucleus of mass number 3; He^4=helium nucleus of mass number 4; Li^6= lithium nucleus of mass number 6; Li^7=lithium nucleus of mass number 7; Be^8=beryllium nucleus of mass number 8. γ denotes that a γ-ray photon is given out in the reaction. Tritium is radioactive; it decays into He^3 with a half-life of 12.4 years.

APPENDIX III

THERMONUCLEAR REACTIONS IN STARS

It had long been apparent that the source of energy of the stars could conceivably be only a nuclear process. The first quantitative theory was given by H.A. Bethe and G. Gamow in 1938. The light of the stars is a consequence of thermonuclear reactions taking place in stellar interiors where temperatures approach a few ten-million degrees[1]. The two most important reactions in astrophysics are[2]: (*i*) proton-proton reaction in which hydrogen is converted to deuterium, and (*ii*) the so-called 'carbon-nitrogen cycle' where carbon nuclei only serve as 'catalytic agents' for the conversion of ordinary hydrogen into helium. Exact calculations show that in the case of the sun the energy is mostly derived from proton-proton reaction but for hotter main sequence stars the C-N cycle is likely to provide most of the energy.

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[1] It is worth mentioning that the fundamental reason why stellar interiors remain hot enough for thermonuclear reactions to take place—it is most fortunate for us that they do so—is that the stars are so big. For instance, the sun is about a million times more massive than the earth. It is because of this hugeness that it becomes extremely difficult for the heat to leak from inside to the outside of the star with the result that the surface temperature is a few thousand degrees but the deep inside-temperature a few ten-million degrees. It is on the basis of such considerations that one can show that there is no possibility, *not even a remote one*, of 'setting the oceans of the earth on thermonuclear fire'. [See for instance, M.H.L. Pryce, *Discovery*, **16**, 495 (1955)].

[2] See for instance, S. Chandrasekhar, *Astrophysics*, edited by J.A. Hynek, p. 598 (McGraw-Hill, 1951).

Proton-proton reaction	Carbon-nitrogen cycle.
$H^1 + H^1 \longrightarrow H^2 + \beta^+ + \nu_0$	$C^{12} + H^1 \longrightarrow N^{13} + \gamma$ $\downarrow$ $C^{13} + \beta^+ + \nu_0$
$H^1 + H^2 \longrightarrow He^3 + \gamma$	$C^{13} + H^1 \longrightarrow N^{14} + \gamma$
$He^3 + He^3 \longrightarrow He^4 + 2H^1$	$N^{14} + H^1 \longrightarrow O^{15} + \gamma$ $\downarrow$ $N^{15} + \beta^+ + \nu_0$
	$N^{15} + H^1 \longrightarrow C^{12} + He^4$

It is likely that nuclear reactions are also taking place in the outer atmospheres of a few exceptional stars but the mechanism is not as yet clear[3]. They cannot, of course, be thermonuclear on account of the relatively low temperatures involved. The energy generation (erg per sec per gm) due to the proton-proton reaction in a mass of hydrogen at a density of 100 gm per cc is 0.2 for a temperature of 5 million deg. C and 50 for 15 million deg. C. Whether it is the stellar interior or a thermonuclear explosion on the earth, hydrogen and/or its isotopes is a necessary constituent of any such process. The theory of thermonuclear reactions has far-reaching astrophysical importance and had been investigated by astrophysicists in considerable detail several years before it found application in nuclear weapons[4].

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[3] W.A. Fowler, *et al.*, *Astrophysical Journal Supplement Series*, No. 17 (1955).

[4] The basic theories of stellar energy generation and fusion explosions being the same, one often comes across Atomic Energy Weapons Establishments advertising for theoretical astrophysicists.

CHAPTER III

FISSION ENERGY AND RADIOACTIVITY OF FISSION PRODUCTS

In the preceding chapters we have spoken of the tremendous energy released in nuclear explosions. The nuclear process (fission or fusion) takes place in a comparatively small mass of some suitable material. Thus, for instance, the energy of the Hiroshima bomb, equivalent to 20,000 tons of TNT, was liberated as a result of fission of about 2 pounds of uranium 235. The actual amount of uranium 235 used in the bomb was very much larger, but, except for the two pounds which suffered fission, the rest was merely dispersed into the atmosphere. In this chapter we shall first deal with the energy released in fission and then consider the radioactivity of fission products. This will provide the necessary physical background for the chapters to follow.

Fission Energy

The fission of a single nucleus of say, uranium 235, produces a total energy very nearly equal to 200 mev. The kinetic energy of neutrons emitted during the act of fission is about 2.5 percent. These are called *prompt neutrons*, to distinguish them from delayed neutrons emitted from a small fraction of a second to several seconds after the fission act. The *delayed neutrons* are not more than about a few percent of the number of prompt neutrons. The energy of prompt gamma rays is about the same as the energy of prompt neutrons. About 3 percent is the energy of gamma rays emitted from the fission products, and about the same is the energy of beta rays emitted from them. Table V gives the distribution of energy from fission of uranium 235 caused by the capture of slow neutrons.[1]

TABLE V

Distribution of energy in slow-neutron fission of uranium 235 (energy unit: mev)

Instantaneous		Delayed	Total
Localised in space	Fission-product kinetic energy =168±5	Fission-product betas=7	175
Spread out in space	Neutron kinetic energy=5±0.5 Fission gammas =4.6±1	Fission product gammas=6	16
Total	178	13	191
Neutrino energy 11 mev (not available as heat source)			11
Total			202 mev

When a nuclear explosion takes place it is only about 90 percent of the total fission energy which appears as the energy of the explosion. The remaining 10 percent constitutes the energy of the beta and gamma rays emitted from the fission products and the unavailable energy of the neutrinos, the energy of the gamma rays being 3 percent of the total fission energy.

We can thus readily calculate the explosion energy released in the complete fission of 1,000 kilograms (one metric ton or 2,200 lb) of material:

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[1] *Reactor Handbook*: *Physics,* USAEC, p. 110 (1955).

Fission of 1,000 kg of material ($=2.6\times10^{27}$ nuclear fissions)	gives energy	$=8.4\times10^{23}$ erg $=2.0\times10^{16}$ gm calorie $=2.3\times10^{10}$ kilowatt hour =20 million ton of TNT

(It is also roughly equal to the energy of average sunshine over India for about two minutes).

We now turn to the radioactivity of the products formed in fission.

Fission Products

When fission takes place, say in uranium 235, all nuclei do not fission in an identical way. In fact, it is known that fission takes place in more than 40 different ways producing about 80 different nuclear species or nuclides. The most probable mass numbers for the fission fragments lie around 95 and 139 and these nuclides constitute about six percent of the total fission nuclides. As each nucleus, on fission, gives two daughter nuclei, the total yield of the fission nuclides per 100 fission-acts adds up to 200. The probability of symmetrical fission (fission into equal parts) is very small, only about 10^{-4}. The probability of fission into three equal parts is somewhat more than 10^{-6}. For plutonium 239 the relative proportions of nuclides of different mass numbers in the fission products is almost the same whether the fission is caused by thermal neutrons or fast neutrons ; [the yield *versus* mass number curve shows a fine structure corresponding to the shell structure (so called 'magic numbers') of nuclei]. The yield *versus* mass number curve for fission of uranium 238 (which fissions on capture of fast neutrons only), when compared to the curve for thermal fission of uranium 235, is slightly displaced towards higher mass numbers ; the yield for mass number 90 is about 6 percent for uranium 235 and 4 percent for uranium 238. (*Fundamental*

Chemistry for Nuclear Engineering, USAEC, May 1955).

The primary nuclides are unstable, containing on an average something less than six excess neutrons per pair of primary fragments ; and hence (on an average) the pair undergoes the same number of beta-decays, often accompanied by gamma rays, before stable nuclides are formed.[2]

The fission products constitute a complex mixture of about 100 different types of radioactive nuclides with decay periods varying from a fraction of a second to several years. [Actually the number of nuclides should be much more but they have presumably escaped detection either because of too short a half-life or too long a half-life[3]. The measured half-lives range from 1 second (xenon 144) to 1.7×10^7 years (iodine 129). Some nuclides also

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[2] About 5.4 beta-decays per pair of primary nuclides is an average value. Thus to take a typical instance, uranium 235 fissions into ${}_{40}Zr^{97}$ and ${}_{52}Te^{137}$ which then beta-decay according to the following scheme :

$${}_{40}Zr^{97} \xrightarrow[\text{17hr}]{} {}_{41}Cb^{97} \xrightarrow[\text{75min}]{} {}_{42}Mo^{97} \text{ stable}$$

$${}_{52}Te^{137} \xrightarrow[\text{1 min}]{} {}_{53}I^{137} \xrightarrow[\text{22 sec}]{} {}_{54}Xe^{137} \xrightarrow[\text{3 min}]{} {}_{55}Cs^{137} \xrightarrow[\text{33 yr}]{} {}_{56}Ba^{137} \text{ stable}$$

In some cases as many as six successive beta-decays occur, *e.g.*, ${}_{36}Kr^{97}$ after six betas leads to the stable ${}_{42}Mo^{97}$.

In many cases it is difficult to be certain whether a given fission product is of primary or secondary origin. In this connection the occurrence in fission products of what are called *shielded nuclei* is of special interest; such nuclei (*e.g.*, Br^{82}) cannot arise from a beta-decay because of the existence of contiguous stable isobars (*e.g.*, ${}_{34}Se^{82}$ and ${}_{36}Kr^{82}$, in the case of ${}_{35}Br^{82}$); they are formed as primary products, or maybe as a result of delayed neutron emission.

[3] The half-life T of a radioactive species is the period at the end of which the amount of the radioactive substance left is one-half of its original value. In other words, if N_0 be the number of nuclides at any given time, then after a lapse of period T the number of nuclides left would be $N_0/2$; the other $N_0/2$ would have undergone decay during this period.

decay by neutron emission giving rise to the 'delayed neutrons' referred to earlier].

Decay Rate of Fission Products

The decay rate for this complex mixture is the sum of the exponential decay rates for each nuclear species, the individual decay constants varying over a very wide range. The integrated decay rate cannot obviously be exponential: It follows, however, a rather simple law. Roughly, it *varies inversely as the time t reckoned from the instant of detonation.* A better approximation is to take 1.2 for the power of t instead of unity. The rate of emission of gamma ray photons and beta particles is given by (the error in the expressions is not likely to exceed by a factor of 2, possibly less):

Rate of emission of gamma ray photons
$= 1{\cdot}6/t^{1{\cdot}2}$ photons per second per fission

Rate of emission of beta particles
$= 3{\cdot}2/t^{1{\cdot}2}$ particles per second per fission

where t is the time in seconds after the instant of fission. The expressions are valid from about 10 seconds after fission ; and though the exponent of t depends somewhat on the duration, it is sufficiently accurate for our purpose to take the value to be 1.2 for all values of t after about 10 seconds.[4] The average energy of beta particles is about

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[4] H.F. Hunter and N.E. Ballou, *Nucleonics*, **9**, C-2 (1951) have examined in detail the decay rate of fission products for uranium 235. Their results are summarized below:

Let $A(t)$, where t is in *minutes*, represent disintegrations per minute from fission products formed from 10^4 fissions at $t=0$.

$A(t)=2{,}800\ t^{-0.89}$	$1\ \text{min} \leq t < 30\ \text{min}$
$A(t)=5{,}700\ t^{-1.11}$	$30\ \text{min.} \leq t < 1\ \text{day}$
$A(t)=15{,}600\ t^{-1.25}$	$1\ \text{day} \leq t < 4\ \text{days}$
$A(t)=2{,}400\ t^{-1.03}$	$4\ \text{days} \leq t < 100\ \text{days}$
$A(t)=2.16\times10^{6}\ t^{-1.60}$	$100\ \text{days} \leq t < 3\ \text{yr}$

The value of $A(0)$, the actual total activity at zero time ($t=0$) is computed to be 44,000 dpm.

0.4 mev, and of gamma rays 0.7 mev. The rate of emission of energy is $1{\cdot}1/t^{1.2}$ mev per second per fission for gamma rays and the same expression roughly holds for beta rays also.

The above relations can be written in a somewhat different form. Consider a fission explosion resulting in the complete fission of 1,000 kilograms (one metric ton or 2,200 lb) of material, *e.g.*, uranium 235, plutonium 239, uranium 233, or uranium 238. The total mass of fission products will be very slightly less, by about 0.1 percent, than the mass of the original unfissioned material: The difference in mass corresponds to the energy produced in the explosion. According to the Einstein relation, energy=mass × (velocity of light)^2. The *activity in curies* for* 1,000 *kilograms of fission products is*:

$$\text{gamma activity} = \frac{1.1\times10^{17}}{t^{1.2}} \text{ curies } (t \text{ in sec})$$

$$= \frac{6.0\times10^{12}}{t^{1.2}} \text{ curies } (t \text{ in hr})$$

$$\text{beta activity} = \frac{2.2\times10^{17}}{t^{1.2}} \text{ curies } (t \text{ in sec})$$

$$= \frac{12.0\times10^{12}}{t^{1.2}} \text{ curies } (t \text{ in hr})$$

(1 curie$=3.7\times10^{10}$ disintegrations per second)

As $7^{1.2}\sim10$, if the activity at unit time (we can take any unit: minute, hour, day etc.) from detonation be taken as unity, then at 7 units of time the activity is $\frac{1}{10}$; at 7×7 units of time the activity is $\frac{1}{100}$ and so on. Thus, taking the activity at one hour after detonation to be equal to unity, we have (approximately):

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* The curie is a unit of radioactivity (named after the discoverers of radium). 1 curie represents that amount of a radioactive species (nuclide) such that the number of nuclei disintegrating per second is $3.7\text{x } 10^{10}$. The mass of radiocative species corresponding to 1 curie is directly proportional to its half-life. For instance, for radium 1 curie corresponds to 1 gram, the corresponding figure for uranium 238 is 3 tons, and for carbon 14 it is 0.2 gram.

Time	*Activity*
1 hour	1
7 hours	1/10
7 × 7 hours ~ 2 days	1/100
2 weeks	1/1,000
3 months	1/10,000

The fission products contain some nuclides which, because of their relatively long half-life and/or biological considerations, constitute a special hazard (Chapter V). The properties of these nuclear species are given in Table VI. Needless to add that when dealing with the activities of any particular nuclear species the $1/t^n$ law has no meaning, the decay rate being given by the usual exponential law ($e^{-\lambda t}$), where $\left(\frac{1}{\lambda} = \text{mean life} = \frac{\text{half-life}}{0.693}\right)$.

TABLE VI

Radioactive and 'Effective' half-lives of important fission products[5]

Nuclear species	Energy (mev) of emitted radiation		Radio-active half-life. *Tr*	'Effective' half-life *T*	Fission product atoms per 100 nuclear fissions (total fission products =200 atoms)	For 1,000 kilogram of total fission products	
	gamma	beta				Amount in kilogram of fission products	Initial activity in million curie
Strontium 89	None	1·463	53 day	52 day	4·6	18	500
Strontium 90	None	0·61	28 year	7·4 year	5·0	19	2·8
Iodine 131	0·364, 0·284, 0·637	0·608, 0·335	8·0 day	7·5 day	3·1	18	2200
Cesium 137	0·6616	0·523	33 year	17 day	6·2	37	2·9
Cerium 144	0·134, 0·100, others	0·300, 0·170	275 day	180 day	5·3	33	110

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[5] The yields refer to slow neutron fission of uranium 235, but

'Effective' Half-Life

In assessing the radiological hazard from external exposure to a radioactive substance, its radioactive half-life (T_r) is important. However, if a radioactive substance is inhaled or swallowed (ingestion) its presence inside the body would constitute a radiological hazard. The magnitude of this hazard depends not only on the radioactive half-life of the substance but also whether it is rapidly or slowly eliminated from the body. The biological half-life (T_b) is a measure of this rate of elimination. Actually, the biological elimination follows a complex pattern and is not described by a simple exponential decay law. "However, in most cases, after the initial distribution and readjustment of the radio-isotope from one body organ to the other, the decay curve is usually close to a simple exponential." The concept of biological half-life is thus not a clear-cut one. All the same, it is of considerable importance. (A detailed discussion is given in the "Recommendations of the International Commission on Radiological Protection," *British Journal of Radiology. Supplement 6, 1955*). In an assessment of the permissible dose for internal radiation the *effective* half-life (T) defined as

$$\frac{1}{T} = \frac{1}{T_r} + \frac{1}{T_b}$$

(roughly) the same may be assumed to apply in other cases, say within a factor of 2 to 3.

The yield for strontium 90 is not given in *Reactor Handbook: Physics*, USAEC (1955). From the yield *versus* mass distribution curve, we get a value of 5.4 percent for $Sr^{90}+Y^{90}$, in the case of slow neutron fission of uranium 235. We shall assume that the primary yield of Y^{90} is negligible and take Sr^{90} yeild=5 percent. For uranium 238 fission the yield *versus* mass curve gives for $Sr^{90}+Y^{90}$ the value 3.8 percent.

The yield for cesium 137 is also not given in *Reactor Handbook: Physics*, but has been estimated from yield *versus* mass-distribution curve.

is of considerable significance. The values of T are included in Table VI.

Important data for fission energy and radioactivity of fission products are summarized for ready reference in Chart I.

CHART I(a)

ENERGY OF FISSION AND RADIOACTIVITY OF FISSION PRODUCTS

[FISSION OF 1000 KILOGRAM (=2200 lb=1 METRIC TON) OF MATERIAL]

[1 curie $=3.7\times10^{10}$ disintegrations per second]			
1.	Fission of 1000 kilogram	$=2.6\times10^{27}$ fission-acts	$\sim 6\times10^{27}$ neutrons released (mass $\sim$ 10 kilogram)
2.	Energy released in fission of 1000 kilogram = $8{\cdot}4\times10^{23}$ erg $2{\cdot}0\times10^{16}$ gram calorie $2{\cdot}3\times10^{10}$ kilowatt hour 10^{6} megawatt day (3 million tons of coal)	=20 MILLION TONS OF TNT	This is 2 percent of the world's total annual output of electrical energy. Also roughly equal to the energy of average sunshine over India for about 2 minutes.
3.	*Activity* (gamma ray) of fission products (1000 kg) at time *t hours* from detonation	$=\frac{6.0\times10^{12}}{t^{1\cdot2}}$ curie (for *t* from about 10 second to 1 year)	= $8{\cdot}2\times10^{14}$ curie at end of 1 minute $6{\cdot}0\times10^{12}$ curie at end of 1 hour $1{\cdot}3\times10^{11}$ curie at end of 1 day $2{\cdot}3\times10^{9}$ curie at end of 1 month $1{\cdot}1\times10^{8}$ curie at end of 1 year 8×10^{6} curie at end of 10 year
4.	*Activity* (beta ray) of strontium 90 contained in 1000 kg of fission products	$=2.8\times10^{6}$ curie	$\mathrm{Sr}^{90} \xrightarrow[\beta^-_{(0\cdot6\ \mathrm{mev})}\ \text{no gamma}]{28\ \text{year}} \mathrm{Y}^{90} \xrightarrow[\beta^-_{(2\cdot18\ \mathrm{mev})}\ \text{no gamma}]{61\ \text{hour}} \mathrm{Zr}^{90}$ Half-life of $\mathrm{Sr}^{90}=28$ year Half-life $=0{\cdot}693\times$ average life

CHART I (b)

TIME VARIATION OF ACTIVITY OF FISSION PRODUCTS [DOSE RATE IN ROENTGENS]

5† *Dose Rate* of 1 roentgen per day(=0.04r/hr) (The dose at a distance *d* cm from a point source of 1 gm of radium in equilibrium with its disintegration products and shielded with 0.5 mm of platinum is given by the expression:

$$\text{dose}=\frac{8.4\times10^{3}}{d^{2}}\ \text{roentgen per hour})$$

corresponds to 10,000 curie per sq mile

= $\left\{\begin{array}{l} 3.6\times10^{-4} \text{ curie per sq ft} \\ 3.9\times10^{-7} \text{ curie per sq cm} \\ 2\times10^{12} \text{ curie spread uniformly over the surface of the earth (200 million square miles)} \end{array}\right.$

6† *Dose Rate* $r(t)$ at time t from detonation is equal to $\frac{\text{constant}}{t^{1\cdot2}}$, for t from about 10 second to 1 year

Total dose received from time t to T

$$=5t^{1\cdot2}\, r(t) \left(\frac{1}{t^{0\cdot2}} - \frac{1}{T^{0\cdot2}}\right),$$

$$=t^{0\cdot2}\, R(t) \left(\frac{1}{t^{0\cdot2}} - \frac{1}{T^{0\cdot2}}\right),$$

where $R(t)=5t\, r(t)$ is the total dose received from t to eternity

Time-decay of activity of fission products

Time	Activity
1 hour	1
7 hour	0.1
1 day	0.02
2 day	0.01
2 week	0.001
3 month	0.0001

Fraction of 'eternity dose' (taken to be unity) received from 1 hour to time t

Time	Fraction of eternity dose received
1 hour	0
6 hour	0.30
1 day	0.47
1 week	0.64
1 month	0.73
1 year	0.84
eternity	1.00

7† From 5 and 4, we have: Sr^{90} *content* in curie per sq mile

$= 0.11 r(t) t^{1\cdot2}$; t *in hour*, $r(t)$ is dose rate in roentgen per hour

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† See Chapter V for explanation of 5, 6 and 7.

CHAPTER IV

EFFECTS OF ATOMIC BOMB

Hiroshima-Nagasaki Bomb

August 6, 1945, is an unforgettable date: It was on the early morning of this day that the first atomic (U235) bomb fell on Hiroshima, killing 78,000 men and injuring another 37,000. The second atomic (Pu239) bomb was dropped on Nagasaki on August 9, 1945. The number killed was 24,000, and injured 23,000. The two bombs were of about the same power, equivalent to 20 *kilotons of TNT*, but due to the rather uneven terrain in Nagasaki casualties were less there. The bombs were exploded at about 2,000 feet above ground to obtain, as nearly as possible, the maximum area of damage due to the blast of the explosion. The death rate was above 90 percent within ½ mile of ground zero (the point on the ground immediately below the burst), about 50 percent between ½ mile and 1½ miles, and not more than about 1 percent beyond 1½ miles. Structural damage was complete (including collapse of earthquake-resistant reinforced concrete buildings) within ½ mile from ground zero, and most of the houses within 1½ miles were destroyed. Houses up to 2 miles were badly damaged, and slightly damaged up to about 3 miles. The explosion, because of the very high temperature produced, emitted intense heat radiation causing fatal burns (and almost instantaneous deaths) to exposed persons within about ¾ mile of ground zero. Though, in general, most of the Japanese A-bomb casualties were due to the combined effects of burns and mechanical injuries, it is estimated that about 60 percent of the deaths (and at least 75 percent of all casualties) were due to burning (heat flash and fires), about 20 percent due to physical injuries from falling structures and flying debris (as a result of blast-damage) and 20 percent due to other causes including nuclear radiation (gamma rays).

At the close of the Japanese war the *US Strategic Bombing Survey* made a detailed study of the damage inflicted by the two A-bombs, and their reports, *The Effect of the Atomic Bomb on Hiroshima, Japan*, Vols. I, II and III (1947) and *The Effect of the Atomic Bomb on Nagasaki, Japan*, Vols. I, II and III (1947), provide most valuable information on the subject. A British mission also visited the two cities and published a report entitled *Effects of the Atomic Bombs on Hiroshima and Nagasaki* (H.M.S.O., 1946).

In 1950 the Los Alamos Scientific Laboratory (operated by the University of California for the US Atomic Energy Commission) published its handbook of over 450 pages on *The Effects of Atomic Weapons*[1] (prepared for and in co-operation with the US Department of Defence and the US Atomic Energy Commission). It is based on the experience of Hiroshima-Nagasaki and on the results of test explosions, particularly the 1946 Bikini tests (*air burst* 'Able' on July 1 and *shallow underwater burst* 'Baker' on July 25). The purpose of the handbook, so far the most authoritative open publication on the effects of atomic weapons (in the energy range of kilotons), was to present, as accurately as possible in the light of existing knowledge, a technical summary of the results to be expected from detonation of atomic weapons, in order to promote intelligent public understanding and to serve as a guide to technical personnel engaged in civil defence activities in the preparation of practical plans for atomic weapons defences. The present chapter is largely based on this publication. The March 1954 test explosions in the megatons range have, however, rendered this important publication so soon out of date. The fundamental reason is that, whereas for a nuclear weapon in the *kilotons* range the radiological effects compared to blast and heat effects are relatively of minor importance, in the case of a *megatons weapon* the radiological effects far outweigh anything else. This is the new situation, and the difference is a radical one. However, to bring out this point more clearly, let us first briefly consider the effects of kilotons weapons.

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[1] This publication will be referred to here as AW (1950).

Kilotons Weapons

Atomic weapons, that is, missiles in which the energy is obtained from the detonation of a self-sustained fission process (see page 16), can now be made covering a wide range of explosion energies, say, from ½ kiloton to 500 kilotons equivalent of TNT. It is likely that the relatively low-energy ones are made of uranium 233 which has a substantially smaller ' critical mass ' than uranium 235 or plutonium 239. Below about 5 kilotons, the use of fissile material is not very efficient. Missiles under about 5 kilotons are likely to be ' atomic shells' fired from large-calibre guns ('atomic gun') whereas larger sizes would be used in rockets (free-flight or guided) or delivered as bombs. The range of the atomic gun may be about 20 miles and its accuracy (50 percent zone) about 100 yards, the weight of the shell being of the order of ½ ton. In the case of a guided rocket, the range may be 100 miles and its accuracy about 200 yards, the weight of the complete rocket being about 5 tons (the war-head weighing about a ton).

Nominal A-Exposion : Air Burst

In discussing the effects of atomic weapons it is usual to consider an explosion of energy equivalent to 20 kilotons of TNT. This is called a *nominal atomic explosion* (or nominal A-bomb). The effects of the nominal A-bomb have been dealt with at considerable length in

AW (1950). Fairly reliable scaling laws (e.g., the so-called cube-root law for blast effect) have been worked out for readily estimating in terms of the data given for the nominal A-bomb the probable effects of bombs of other sizes.

The explosion energy of the nominal bomb is that liberated in the complete fission of one kilogram (2.2 lb) of fissile material (uranium 235, plutonium 239 or uranium 233). As described in Appendix I, the actual amount of fissile material contained in the bomb would be much larger, say 5 to 10 times larger, as it is only a fraction of the total fissile material that actually undergoes fission in an explosion.

The effects of nuclear weapons can be classified under four major heads:

Effects of Nuclear Explosion

	Blast	Thermal radiation: *Heat flash*	Initial nuclear radiation: (*neutrons and gamma rays*)	Residual nuclear radiation (gamma rays and beta rays): *Fallout*
Duration of effects	less than a minute			days—months—years

About 6 percent of the total explosion energy is carried away by the prompt neutrons and gamma rays, divided nearly equally between them: These are emitted simultaneously with the act of fission, and hence their emission lasts only for the duration of the detonation (a few microseconds). About 3 percent is the energy of the gamma rays emitted by the fission products in the first minute of the explosion. This also is included under the head 'initial radiation'. Most of the total energy, roughly about $\frac{2}{3}$ in the case of air burst, goes into blast, and about $\frac{1}{3}$ is emitted as thermal radiation.

Let us consider an *air burst*, that is, a burst at a height of say 2,000 feet above the surface: (If the height is less than about 500 feet it is called a surface burst). The first announcement of the detonation is a brilliant white flash many times brighter than the sun. The tremendous energy released in the explosion reduces practically everything—the contents and the casing of the bomb—to a gaseous state. Initially the mass, which has about the same volume as the original size of the bomb, is at a temperature of over a million degrees and a pressure over a million atmospheres. At about 0.1 millisecond from the instant of detonation, it is an isothermal sphere of diameter about 30 yards and temperature 300,000 deg.C which is 50 times the surface temperature of the sun. At this stage the shock-front of the blast wave coincides with the surface of the sphere, but soon the shock-front 'breaks away' and moves ahead. The surface of the fire ball cools rather rapidly (because of the energy lost by it on account of radiation into space) and in a little more than 0.01 second, the surface temperature reaches its minimum value of about 2,000 deg.C. The interior of the fire ball is still very hot. As the air surrounding the sphere gets heated and ionized by the advancing shock-front, its transparency falls and it exerts a 'blanketing effect' on the hot sphere. The rate of loss of heat from the surface decreases and, as the flow of heat from the inside continues, the surface temperature begins to rise. It reaches a second maximum of about 7,000 deg.C at about 0.3 second, and at the end of about 10 seconds the luminosity is almost extinct. The maximum rate of ascent of the fire ball is about 300 feet per second. The diameter slowly continues to increase and attains its maximum value of about 300 yards in about one second.

The break-away of the shock-front is soon followed by a wave of low pressure causing expansion of the air and consequent condensation of any water vapour contained in it. "What is seen is a ring of fog, spreading outwards at the speed of sound and lit up, like a Chinese lantern, by the red glow of the fire ball inside it. Within a few seconds the pressure returns to normal and the condensation cloud suddenly disappears. The fire ball is then seen, rushing upward at a speed of a hundred miles per hour. It is followed by an opaque cloud of turbulent gases mixed with dust drawn from the surroundings by the uprush of air. The rising cloud reaches the stratosphere in about four minutes and, continuing upwards, rises to its full height of thirty to sixty thousand feet in about seven minutes. By this time the fire ball has disappeared and has been replaced by a mushroom-shaped cloud of white vapour which eventually reaches a diameter of two miles. At Bikini the mushroom persisted for many hours and was followed by planes with Geiger counters as it slowly drifted downwind."*

Heat Flash

We have already said that roughly $\frac{1}{3}$ of the total energy goes into the heat flash. About 99 percent of the radiation is emitted by the sphere after it has attained the minimum temperature and there is practically no radiation after about 3 seconds. (The radiation emitted before the minimum temperature is negligible because this stage is reached within a fraction of a second of the detonation and thus the time available for radiation is very little). If protection is found within 1 second of the explosion, the radiation received would be about $\frac{1}{3}$ of the total. The radiation received from the heat flash would be about 6 gm cal/cm^2 at a distance of a little more than 1 mile on a moderately clear day and $\frac{1}{2}$ mile in dense haze — the range of heat effect depends very much on the *visibility* of the atmosphere. This exposure would cause 50 percent immediate deaths. White paper burns at 10 gm cal/cm^2 and black paper at 3 ; wood burns at about 10 gm cal/cm^2, but the figure varies with the nature of wood. The ground temperature below the point of burst rises to 3,000 deg.C.

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* *Admiralty Notes on Atomic Energy for Medical Officers*, H.M.S.O., 1955, p. 68.

If E be the total thermal radiation emitted in the heat flash, then the heat Q received at a distance D is

$$Q = \frac{E}{4\pi D^2} \exp(-kD)$$

where k represents the mean-attenuation-coefficient and is an average for the spectrum of radiation extending from $\lambda \sim 2{,}000$ Angstroms to infinity. Strictly, therefore, k is not a constant, but depends on D. However, for our present purpose it can be taken as constant. The value of k is about 2 km^{-1} in a dense haze and 0.1 km^{-1} in an exceptionally clear atmosphere ; but in general k is about 0.4 km^{-1} on a moderately clear day. (The visibility range $L \sim \frac{4}{k}$ km). The total explosion energy for a nominal A-bomb is 2×10^{13} gm cal, and assuming E to be $\frac{1}{3}$ of the above value, we have

$$Q \sim \frac{670}{4\pi D^2} e^{-kD} \text{ gm cal/cm}^2$$

where the distance D is in kilometers.

Blast

The first effect of a blast wave on a structure is that of a gigantic hammer blow. When the shock-front of the blast wave reaches the rear end of the structure, it is completely surrounded by the wave and the effect of the blast pressure is to squeeze or crush the structure: The damage to the structure depends on its strength and partly on its shape, number of openings etc. The duration of the blast pressure is of the order of a second, and is thus more than hundred times what it is for a conventional bomb (*e.g.*, a blockbuster). The spatial extension of the positive pressure phase is about 1,000 feet; the negative phase is a few times longer, but *unlike the* *case of conventional bombs*, its damage effect is negligible when compared to the positive phase. In the case of conventional bombs, the damage inflicted by a blast wave is essentially determined by the impulse of the blast, i.e., (average) pressure multiplied by the duration of the blast. In the case of atomic bombs the duration of the blast is so much more that the damage is largely determined by the peak-pressure of the blast and not by the impulse.

The blast wave or shock-wave spreads outwards with a velocity which is initially over a mile per second but soon falls to the velocity of sound ($\frac{1}{5}$ mile/sec). The peak-pressure (maximum pressure in excess of the atmospheric pressure) exerted by the blast wave is about 20 lb/in.^{2} at $\frac{1}{2}$ mile from ground zero. An over-pressure of this magnitude is enough to destroy completely all structures, except perhaps the very strongest. At 2 miles the pressure drops to less than 2 lb/in.^{2} which can only cause minor damage.

It is interesting to observe that a blast, as such, will hardly injure a person seriously; the casualties due to blast arise not because of its direct effect on the human body but on account of the injuries caused by falling structures, flying debris, glass etc. "The human body is remarkably resistant to damage by a blast wave in air. Ear drums are by far the most vulnerable point, and these burst when the peak-pressure in the blast is from 5 to 15 lb/in.^{2}, depending on the direction of the head with respect to the blast and on the individual. At very much higher peak-pressure, of the order of 200-250 lb/in.^{2}, general damage of a serious type is caused[2]. Haemorrhage is caused in the lungs and at other places where tissue has an internal boundary surface with an air or gas cavity. Damage of the same type is caused to minor animals swimming on the surface, or under the surface, from underwater explosions, and the critical peak-pressure is of the order of one ton to the square inch. Small animals are more vulnerable to air blast than large ones. Mice succumb from lung haemorrhages at about 25 lb/in.^{2} shock over-pressure. The duration of the blast appears to be relatively unimportant provided it is short. The outstanding hydrodynamical problem is the solution of the propagation of finite pulses through a material like lung tissue, cork, sorbo-rubber or foam."†

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[2] Even at 500 ft from ground zero the blast peak-pressure (for 2,000 ft high air burst) is only 50 lb/in.^{2}.

In the case of an air burst the blast constitutes the most important effect of the A-bomb, at any rate, so far as material destruction is concerned. In its details the blast phenomenon is extremely complex, and a good deal of this complexity is due to the interaction between the primary and the reflected shock-waves (leading to the formation of what is called the Mach stem or fused shock)[3]. When a shock-wave suffers a head-on reflection (normal incidence), the over-pressure (due to reflection) is increased by a factor which is not much above 2 for over-pressures below 10 lb/in^2.— weak shock, i.e., the 'acoustic approximation' — but approaches 8 for strong shocks. For a *crude estimate* of the range of blast damage for a given size of nuclear weapon in terms of the 'known' — from Hiroshima-Nagsaki experience and test explosions — radius for the nominal A-bomb, use is often made of the *scaling law* which can be stated as follows :

The pressure, density and temperature at a distance r from the centre of detonation and at a time t (t is measured from the instant of detonation) depend on r and t, and the blast energy w of the explosion, but this dependence can be completely expressed in terms of the quantities $r/w^{\frac{1}{3}}$ and $t/w^{\frac{1}{3}}$. This is the so-called *cube-root scaling law.* The blast energy w can be taken (on an average) to be about $\frac{2}{3}$ of the total energy (W) released in the explosion, but this proportion is somewhat more for lower values of W.

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† W. G. Penney and H.H.M. Pike, *Report on Progress in Physics*, **XIII**, 81 (1950).

[3] "As a working approximation, the height of burst will be chosen so as to achieve a desired stem height at a specific peak over-pressure on the ground" (AW (1950), p. 80).

We have already mentioned that for a nuclear explosion the criterion of blast damage is the peak-pressure of the blast wave, and hence it follows from the *scaling law* that *the radius of blast destruction is proportional to the cube-root of the explosion energy*: The area of blast destruction is proportional to $W^{\frac{2}{3}}$. (In the case of conventional bombs, the damage criterion is the impulse of the blast; and hence the radius of destruction, as again is obvious from the scaling law, is proportional to $W^{\frac{2}{3}}$, and the area varies as $W^{\frac{4}{3}}$)[4].

The following table gives the radius for severe damage for 5, 10 and 20 kiloton explosions: Severe damage means that the 'equipment' is rendered useless and is not repairable without removal to a major repair facility.

Radius of blast damage

Item	Severe damage (radius in yards)		
	5 kt	10 kt	20 kt
Men in the open ..	800	1,100	1,400
Men in built-up areas ..	600	800	1,000
Tanks	120	150	200
Vehicles	600	800	1,000

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[4] The subject of shock hydrodynamics and blast waves is one of the most important and difficult branches of mathematical physics. The study began with the great work of Riemann in the last century. Amongst some of the most outstanding contributions, mention may be made of the work of G. I. Taylor, J. von Neumann and W. G. Penney. [A review of some of the recent work is given by Penney and Pike in *Report on Progress in Physics*, **XIII**, 81 (1950)].

It is interesting to recall that for 1,000 lb M.C. (conventional high explosive) bombs, the *vulnerable area* against tanks is only about 300 square yards, i.e., a tank is vulnerable to the bomb if it explodes within about 10 yards of the tank. Against aircraft on the ground, the vulnerable area is about 10,000 square yards.

The immediate effects of the A-bomb may be regarded to be over in about 10 seconds of detonation. The luminosity of the fire ball would have almost died out by that time. The blast wave would have travelled more than 2 miles and the pressure fallen to a harmless level. The heat flash would not last beyond about 3 seconds. The initial effects of nuclear radiation would also have been very nearly over (see below). (For megatons bombs the durations would be roughly 10 times longer).

Radiological Effects

We now come to the radiological effects of the A-bomb. It is usual to consider the effects under two heads : (i) *initial effects* (i.e., effects arising in the first one minute of detonation) and (ii) *residual effects* (i.e., effects arising after one minute). The time limit of one minute is, of course, arbitrary; but as the blast and heat effects of a nominal A-bomb last for only about 10 seconds, and as a minute is a reasonable duration within which one could seek shelter or protection (if available) to cut down substantially the harmful effects of nuclear radiation, the dividing line at one minute between *initial* and *residual* effects is a convenient one for practical purposes.

Let us first take the initial effects. The *initial* nuclear radiation consists of (i) *prompt* radiation (gamma rays and neutrons) emitted in the actual fission process and also a relatively small proportion of gamma rays liberated in radiative capture and nuclear excitation due to collisions between neutrons and atomic nuclei — it all arises within a few microseconds of the instant of detonation — and (ii) gamma rays emitted by the fission products in the first minute of detonation, these being a part of what have been called delayed gamma rays in Table V. (The number of delayed neutrons is less than one percent of prompt neutrons and can thus be completely ignored). The initial radiation also contains beta rays—the total energy is of the same order as for gamma rays — and a small proportion of alpha rays, but as their range in air — the distance they can penetrate — is comparatively very small, these constitute no hazard in practice, and hence we shall be only concerned with gamma rays and neutrons.[5] (Beta rays and alpha rays can cause injury if radioactive substances emitting them are deposited on the skin or inside the body).

The prompt gamma rays contain about three percent of the explosion energy, and the kinetic energy of the neutrons is also about the same (Table V). The prompt gamma rays are liberated during the actual process of fission which in a bomb lasts for only a few *microseconds*: They are emitted before there has been time enough for the bomb to be blown apart and hence are practically completely absorbed by the bomb materials (including the casing). They thus have a negligible role in determining the major effects of the initial nuclear radiation. *The same does not apply to the delayed gamma rays.* They come from the fission products and are emitted at a relatively much later stage of the explosion when everything, including the fission products, is volatilized into the expanding fire ball, and hence a considerable fraction of them (practically all) escapes into the atmosphere. (The *average* energy of the delayed gamma rays is about 0.7 mev). If we suppose that a fraction q of the total explosion energy (W) (q is certainly less than $\frac{3}{100}$) is present in the *initial* gamma rays which escape from the fire ball (and the radioactive cloud which succeeds it) into the atmosphere, then the gamma radiation received per unit area at distance D from the explosion is

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[5] Alpha rays have a very small penetrating power, being stopped even by a thin tissue paper. The beta rays have a range of a few yards in air: They are almost completely absorbed by about 0.05 inch layer of wood, water or tissue. The effect of alpha and beta rays is thus unimportant unless the radioactive substances emitting them are in close contact with the skin or deposited inside the body. Gamma rays, on the other hand, are extremely penetrating.

$$\frac{q\,W}{4\,\pi\,D^2}\,e^{-kD}$$

where k is the mean attenuation coefficient. If E mev be the average energy of the gamma ray photons, and as a flux of $\frac{2\times10^9}{E}$ photons per cm^2 corresponds to a dosage of one roentgen (for E lying between about 0.08 — 2.5 mev), we have for the dosage in *roentgens** received by an unprotected person at a distance D kilometers

$$\frac{qW\,e^{-kD}}{4\pi D^2\times10^{10}\times2\times10^9\times1.6\times10^{-6}}\sim 3.1\times10^{-14}\,\frac{qW\,e^{-kD}}{4\pi D^2}\text{ roentgens}$$

We shall now make an estimate for q. The total energy per fission of the delayed gamma rays emitted by fission products is about 6 mev (Table V). From the expression given on page 46 for the rate of decay of the activity of fission products — it holds from about 10 seconds after detonation — we find that the energy going into gamma rays emitted from 1 minute onwards is 2.4 mev, and further the energy emitted between 10 seconds and 1 minute is 1.1 mev. Thus about 3.6 mev is the total energy of the initial gamma radiation emitted from the instant of detonation to 1 minute and this represents about 1.9 percent of the total fission energy. Also, as is obvious from the above figures, about $\frac{1}{3}$ of the total initial gamma ray energy is liberated between 10 seconds and 1 minute, the remaining $\frac{2}{3}$ being liberated before 10 seconds. It is of considerable interest to compare these theoretical estimates with the results of test observations. On the basis of observations made in test explosions it has been found that the dosage from a nominal A-bomb air burst for distances, say, from 2,000 to 9,000 ft, is reasonably well given by the expression[5]

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* See page 78 for definition of roentgen : See also Appendix VI.

$$3.5 \times 10^4 \frac{e^{-3D}}{D^2} = 4 \times 10^{11} \frac{e^{-(10^{-3}D_1)}}{{D_1}^2} \text{ roentgen,}$$

where D is in kilometers and D_1 in feet (AW (1950), p. 235). This means that q is about 1.7/100 as against a theoretical estimate of 1.9/100. This is too close an agreement, and is no doubt partly accidental. Because of the presence of the exponential factor, the dosage drops rapidly with distance. It is 10,000 r at 2,100 ft; 400 r at 4,200 ft; and below one r beyond 9,000 ft. A dose of 400 r would be lethal to about 50 percent of those exposed to it. Thus the hazard due to initial gamma rays is negligible at about 1½ miles from the explosion.

Mention may also be made here of the observation (Bikini 1946 tests) recorded at about 4,200 feet from the explosion (where the dose was 400 r) that about ½ of the initial gamma radiation was received during the first second. "Taking shelter quickly behind a convenient building or in a slit trench — an act which is conceivable within a second of seeing the bomb flash — might thus mean the difference between life and death to a human being at a point where the unprotected dosage would be near the median lethal value".

The average gamma rays (0·7 mev) from fission products are reduced in intensity to ½ of the original value after traversing about 200 yards of air or 9 inches of wood or about the same thickness of body tissues. The following table gives thicknesses of various materials which cut down the gamma ray intensity to a given fraction of the original value :—

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[5] As the gamma rays are heterogeneous, not monochromatic, k in the attenuation factor e^{-kD} would depend on D, and if the variation of D is large we cannot, even approximately, regard k as constant.

The softer components are more strongly absorbed; and at a distance greater than about 3,000 ft the average gamma ray energy is about 3 mev, although rays of energy as high as 4.5 mev are also present.

TABLE VII

Reduction factor for 4.5 mev and 0.7 mev gamma rays

Reduction Factor	Thickness in inches.							
	4·5 mev gamma				0·7 mev gamma			
	Water	Concrete	Iron	Lead	Water	Concrete	Iron	Lead
0·2	30	11	3·8	1·6	12	5·1	1·8	0·7
·1	40	15	5·2	2·3	16	6·8	2·4	1·0
·02	70	25	8·3	3·9	25	11	3·9	1·7
·01	80	30	9·5	4·6	29	13	4·5	2·0
·001	110	40	14	6·7	41	19	6·4	3·1

(Data taken from AW(1950), p. 233)

We now consider the effect of neutrons. As already mentioned, the kinetic energy of the neutrons is about three percent of the total explosion energy. Because of collisions with the molecules of the atmosphere, neutrons are slowed down as they travel outwards by a process of diffusion from the explosion-centre. However, as nitrogen nuclei readily capture neutrons (resonance capture) of energy less than a few-tenths of an electron-volt (and produce redioactive carbon 14) the slowing down process cannot proceed lower than about 0.2 ev. The number of neutrons n (fast, above 3 mev ; slow, about 0.2 ev ; intermediate 0.2 ev to 3 mev) incident per cm^2 at a distance D (km) is roughly given by the expression

$$n \sim \frac{N \times 10^{-10}}{4\pi D^2} \; e^{-D/\lambda}$$

where N and λ are tabulated below (AW (1950), p. 243).

	Fast (above 3 mev)	Intermediate (0.2ev to 3mev)	Slow (0.2 ev)
Apparent neutron source strength	3×10^{22}	3×10^{23}	3×10^{23}
Apparent mean-free-path (km)	0.19	0.18	0.18

An exposure of about 5×10^{11} slow neutrons per cm^2 which corresponds to about 500 rem (Chapter V) is usually considered as lethal. This implies that the lethal range of neutrons from a nominal A-bomb is about 600 yards, and if we include the contribution of fast and intermediate neutrons, the lethal range is about $\frac{1}{2}$ mile.

The total number of neutrons liberated from a nominal A-bomb can be taken as 6×10^{24}, roughly twice the number of nuclear fissions. This number is about 10 times larger than the total N given in the above table. Even if we assume that N were 10 times larger — this assumption is hardly reasonable as a large proportion of the neutrons would undergo capture by nitrogen nuclei — the lethal range, because of the presence of the exponential factor, would still be well under 1 mile.

As most of the neutrons produced would ultimately be captured by nitrogen nuclei, the total amount of carbon 14 produced from a nominal A-bomb would correspond to an activity of about 600 curies.*

It still remains to consider the effect of the residual nuclear radiation, gamma and beta rays, emitted by the fission products one minute after the explosion. (The effect of the nuclear radiation emitted during the first minute has already been discussed above under the head of *initial radiation*). The fission products, because of the intense force and heat of the explosion, are dispersed into extremely fine particles and, most of them being volatile, are reduced to a gaseous state. In the case of an air burst not much dust and debris, comparatively speaking, is sucked from the ground into the fire ball and as such there are not sufficiently numerous and big particles for the radioactive vapours to condense upon. The vapours in consequence condense into very small particles which take a long time to fall to the earth. During all this time the radioactivity of the fission products continues to fall according to the $1/t^{1.2}$ law discussed in an earlier chapter and further because of the actions of the wind and weather the fission products are carried to the farthest ends of the earth (but in general, confined to the latitude of the explosion site). When they ultimately reach the earth — maybe very often carried down by rain — the radioactivity has already decreased to an appreciable extent and since the fallout in this case is distributed more or less over an extremely wide area, its effect at any particular place is reduced to negligible proportions. Such a general fallout must be distinguished from a local fallout which is mainly confined to the vicinity of the explosion. In the case of an air burst the local fallout is negligible.*

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* More about carbon 14 is said in connection with high-yield explosions in Chapter V

It is apparent from what has been said above, that in the case of an air burst of a kilotons weapon the effect of the residual nuclear radiation is of practically no significance. However, this is not quite so in the case of a surface burst or a shallow underwater burst. In the following paragraphs we briefly consider the main effects arising from such bursts, pointing out where they differ from the effects of an air burst.

Types of Burst

A nuclear weapon may be exploded in a variety of different ways depending on the nature of the target and the damage to be inflicted. For instance, in some cases it is desirable to produce a crater in the ground, whereas in other cases it has to be avoided ; in some cases blast has to be emphasized, whereas in other situations it has to be partly sacrificed to secure the utmost of radiological effects. It is usual to consider the following four main types of burst :

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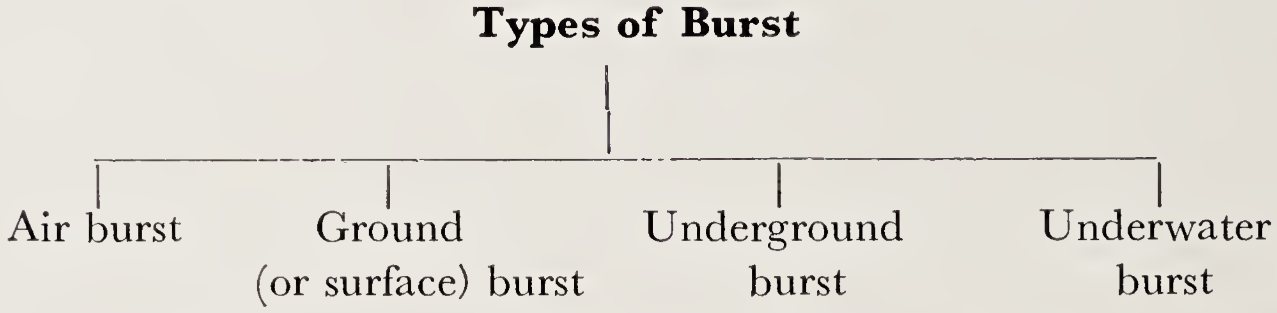
* See page 95 for distinction between local, global and annular fallout.



If the height of burst above ground for a nominal A-bomb is about 2,000 feet, it is called an air burst and if it is about 300 feet (for a bomb k times the nominal bomb the figure would be 300 $k^{\frac{1}{3}}$ feet) it is called a ground burst or low-altitude air burst. For intermediate burst-heights the effect would be in-between that for an air brust and a ground burst. We have already described an air burst. We shall now consider a ground burst.

The essential thing here is that a substantial part of the fire ball comes in contact with the ground. The terrific blast pressure results in the formation of a crater, and a large amount of dust and debris is projected and vaporized into the fire ball and carried upwards in the strong air currents. The size of the crater obviously depends on the nature of the soil, but in sandy soil a nominal A-bomb may make a crater and 'spoil' diameter as large as 400 yards, the depth being about $\frac{1}{6}$ of the diameter. As a part of the blast energy is used up in crater formation, the total area of blast damage is very roughly about $\frac{1}{2}$ of what it is for an air burst. However, the blast pressure near ground zero is much higher for a ground burst than for an air burst, and hence in the vicinity of the burst even the strongest structures suffer utter destruction. The effect of heat flash, because of dust and haze, is much less than for an air burst. The effects of initial nuclear radiation are roughly about the same, but whereas for an air burst there is practically no local fallout, in the case of a ground burst almost (say, 90 percent) the entire quantity of fission products would be brought down by falling dust and debris in the vicinity of the explosion (*local fallout*). The area of local fallout varies considerably with the nature of the ground and meteorological condition at the time: The first determines the quantity of dust thrown into the atmosphere and the second, the direction and distance to which it is carried before returning to the ground.[6] More about this is said in Chapter V. Suffice it to state here that the area of serious radiological hazard due to fallout for a nominal A-bomb would be of the order of 100 square miles. The area of fallout would be an elongated strip along the direction of the prevailing winds. What is relevant is not the surface wind, but the mean of the wind speeds and directions from the surface to a height of about 6,000 feet for a nominal A-bomb and much higher in the case of more powerful bombs.

We now turn to an underground burst.* It has been estimated that a nominal A-bomb exploded at about 50 feet below ground would make in sandy soil a crater and 'spoil' about 700 yards in diameter, the depth being about $\frac{1}{6}$ of the diameter. In ordinary soil the crater diameter would be about 250 yards. The radius of blast damage would be about half to two-thirds, depending on the nature of the soil, of the corrseponding value for an air burst. The radius of blast damage, unlike the radius of crater, is larger for a clayey soil than for a sandy soil. Reflection of the shock-wave by rock strata at depths of 200 to 300 feet is likely to increase somewhat the effect of the blast. The explosion would cause considerable pressures and displacements in underground soil, and the effect on all underground utilities (e.g., sewer, gas and water mains) would be very serious. There is, of course, no heat flash in this case, and no noticeable effect of initial nuclear radiation. The local fallout would in general be confined to a smaller area than for ground burst.

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[6] As an instance of the unusual ways in which fission products can sometimes reach long distances, one may recall the case of fogging of some of the Kodak X-ray films in August 1945. This was traced to a contamination of the straw-board used for packing the films. The contaminant was cerium 141 (one of the fission products) which had travelled *via* the waters of the Wabash river to the straw-board mill a thousand miles away from the explosion site. For details reference may be made to: J.H. Webb, *Physical Review*, **76**, 375 (1949).

* A test of an underground burst of an A-bomb was made by the US in Nevada early in 1955 (*Time*, April 4, 1955).

We have so far been considering bursts on ground and above ground. We shall now take up the case of bursts on water and under water. Here the targets are all forms of surface craft (ships) and underwater craft (submarines). An air burst over water has about the same effects as an air burst over ground. The Bikini 'Able' test (1946) was an air burst over water. The damage to ships is almost entirely due to the effect of the blast, and as is obvious, an air burst inflicts most of the damage to exposed structures (e.g., masts, radar antennae etc.), the radius of very severe damage being somewhat more than ½ mile for a nominal A-bomb.

We now turn to underwater bursts. If the depth of detonation of an atomic bomb is about 1,000 feet below the surface of water, it is referred to as a deep underwater burst. In this case the damage to ships and submarine craft would be caused by the shock-wave transmitted through water and for a nominal A-bomb it is estimated that merchant type ships and light naval craft would be severely damaged up to about 1,000 yards but heavy ships may escape serious damage even as close as 700 yards from surface zero (the point on the water surface immediately above the centre of burst).

The shallow underwater burst is the most imporant of all underwater detonations. The depth of burst is of the order of 50 feet. The Bikini (1946) test

'Baker' was a shallow underwater explosion. The first thing seen was a flash of light, much less luminous than for an air burst, as the fire ball broke through the water surface. A column of water in the form of a hollow cylinder ('plume') with a straight stem and a 'mushroom head' rushed upwards. In 15 seconds it was a mile high and attained its maximum height of about $1\frac{1}{2}$ miles in a minute; the stem was $\frac{1}{3}$ mile in diameter and the 'mushroom head' about $1\frac{1}{2}$ miles across; the water contained in the column was of the order of a million tons. Due to the force of the explosion the water present in the plume was in a state of fine drops, and the subdivision was carried further as the water column began to fall after it had attained its maximum height. From the base of the column there rolled out a white ring of mist (named 'Base Surge') at a speed of about 50 miles per hour. (This was an unexpected phenomenon). After about 3 minutes of the explosion, rain began to fall from the bottom of the expanding surge, and soon the outward spreading slowed down and altogether stopped in another 2 minutes. The base surge probably covered a total area of more than 5 square miles. It carried a part of the fission products, but it is likely that the major fraction of the fission products was in the mushroom top[7].

The base surge constitutes a very serious radioactive hazard for ships in the neighbourhood of the explosion. The material damage to ships is caused by the blast wave produced in water. Unlike the air blast, the shock-wave in water is a high pressure (say, $\frac{1}{2}$ ton in.$^{-2}$) pulse of a very short duration comparable to one hundredth of a second. It is estimated that ships to about

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[7] The theory of the base surge has been recently examined in some detail by E.P. Hicks and W. G. Penney (*Symposium on the Physical Effects of Atomic Weapons*, 1955). They discuss the probable mechanism for the very rapid collection into the rain drops of the very fine drops constituting the base surge, the initial radius of the droplets being about one micron.

$\frac{1}{2}$ mile would be sunk, and moderate to minor damage would extend to somewhat beyond a mile.

As would be expected, a shallow underwater explosion also produces a blast wave in air, the effect being $\frac{1}{4}$ of what it would be for an air burst.

The main conclusion that emerges from the preceeding discussion is that the destruction wrought by an A-bomb is primarily due to its blast effect (leaving aside special situations such as a shallow underwater burst in a harbour attack). It is no doubt true that the colossal difference in the actual weight of an A-bomb and of a conventional bomb-load of equivalent destruction-capacity makes the over-all weapon-systems and weapon-economics radically different in the two cases. In comparing A-bomb and conventional bombs it is interesting to recall that the most devastating raid of the Japanese War was not the atomic bomb attack, but the one on Tokyo using ordinary high explosive and incendiary bombs. Tokyo was raided on March 9, 1945. About 1,700 tons of high explosive and incendiary bombs were sprayed, destroying 16 square miles of the city: 83,000 men were either killed or missing and over 100,000 injured.

For megatons weapons, unlike A-bombs, the radiological hazard becomes of dominating importance. This we take up in the following chapter.

CHAPTER V

EFFECTS OF HIGH-YIELD EXPLOSIONS

In this chapter we describe the blast, heat and radiological effects of high-yield explosions, i.e., explosions in which the energy released is equivalent to millions of tons of TNT. We shall, however, deal here only with the somatic effects of radiation ; the genetic effects will be described in the next chapter. The somatic effect is the injury suffered by the irradiated individual during his lifetime. The genetic effect, on the other hand, depends on the dose received by the gonads only and, unlike the somatic effect, manifests itself not in the exposed individual but in his descendants.

We shall consider for purposes of discussion an explosion of energy equivalent to 20 million tons of TNT (8.4×10^{23} ergs). We refer to it as a nominal high-yield explosion. The energy released in this case is a thousand times more than that in a nominal A-bomb. This is a colossal amount of energy. It is equal to about two percent of the world's total yearly output of electrical energy. Roughly, it is also equal to the average energy of sunshine over India for about two minutes. It is of the same order of magnitude as the amount of energy released in large-scale natural phenomena such as big earthquakes and hurricanes.[1]

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[1] The energy released in earthquakes of different intensities is given below :

	(Mean) Magnitude M on Richter-scale	Energy E (erg)
Great earthquake	8.5	10^{26}
Major earthquake	7.5	10^{24}—10^{26}
Destructive earthquake	6.5	10^{22}—10^{24}

$$M = 1/1.8 \log [E/(2 \times 10^{11})]$$

The kinetic energy of a cyclonic disturbance (10 mb deep

Blast, Heat and Initial Nuclear Radiation

The radius of blast destruction varies with the cube-root of the explosion energy. The same law applies to the duration of any particular phase of the blast wave. Thus, the duration of the positive pressure phase of the blast wave which is about 1 second for a nominal A-bomb is about 10 seconds for a 20 megaton bomb. On account of the long duration of the positive pressure phase the criterion of failure for buildings and structures is the peak-pressure and not the impulse of the blast wave.

The area of damage due to heat flash would be directly proportional to the explosion energy if there were no atmospheric absorption of heat radiation. However, as atmospheric absorption is always present — less on a clear day and more on a hazy day — the ratio of the areas of heat damage for a 20 megaton bomb and a nominal A-bomb is much less than the ratio of their explosion energies. Again, since in the case of the megatons bomb the duration of the heat flash is about ten times longer, that is, 20 seconds or so compared to 2 seconds for a nominal A-bomb—it is much more like a long exposure than a flash—its effectiveness (for the same amount of thermal energy delivered to a surface) is somewhat reduced.[2]

The initial nuclear radiation from a nominal high-yield explosion is about a thousand times more than from a nominal A-bomb. However, on account of atmospheric absorption the relative increase in the area of hazard is

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and 1400 km in diameter) has been estimated to be 1.5×10^{24} ergs, and the kinetic energy of the general circulation of the atmosphere to be 3×10^{27} ergs. [O.G. Sutton, "Thermonuclear Explosions and the Weather", *Nature,* **175**, 319 (1955)].

[2] The rise of temperature of a surface due to the absorption of a given amount of heat radiation roughly varies as $1/\sqrt{t}$, t being the duration of the incident radiation. It is on this account that the heat flash from a megatons bomb, because of its longer duration, is somewhat less effective. [*Nature,* **164**, 923 (1949)].

very much less. It is the presence of attenuation factors of the form e^{-kD} (see pages 57 and 63) which seriously limits the increase in the effective areas of damage due to heat flash and initial nuclear radiation.

We can appropriately scale-up the effects of a nominal A-bomb to obtain a rough indication of the effects for a nominal high-yield bomb. This is provided in Table VIII. As an illustration, we consider an air burst over a city area. The optimum height of burst for a nominal high-yield bomb may be assumed to be about 8,000 feet. The area of blast damage in the case of a ground burst is two-thirds of that in the case of an air burst.

A 20 megaton explosion would destroy completely all ordinary buildings in an area of about 80 square miles; buildings in this area would be 'fractionalized, pulverized or vaporized.' The zone of severe damage would cover more than 200 square miles, and that of partial damage would extend to some 1,000 square miles.

A single bomb would mean virtually complete destruction of even the largest city. For instance, a single 20 megaton bomb dropped on New York would cause material damage of the order of 20,000 million dollars and would result in about 7.5 million casualties. On the basis of rather detailed guess-estimates H. Hart[3] has concluded that the total area of vital strategic targets in the US (such as the US and allied strategic bombing bases; population, business and industrial centres; coal and oil sources; crucial transportation centres etc.) is somewhat less than 2,000 square miles. *Destruction of this vital area would lead to complete national disruption and paralysis.* Speaking of the Soviet stockpile of nuclear weapons, Hart estimates that in 1954 it was large enough to inflict severe damage on an area of about 10,000 square miles, and by 1957 its destruction capacity is likely to be 70,000 square miles, that is, more than thirty times the total area of the US vital targets. And yet this huge figure is based only on the blast effect of the weapons and takes no account of the still greater disaster and distress due to the radioactive fallout from them.

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[3] H. Hart, *Bulletin of the Atomic Scientists,* **10,** 197 (1954).

TABLE VIII

Nominal high-yield explosion[4]

(Air burst at a height of about $1\frac{1}{2}$ miles)

Blast (Duration of positive phase of blast pressure: about 10 seconds)		Heat flash (Duration: about 20 seconds)	Initial nuclear radiation (Duration: about one minute)
Category of damage	Radius of damage (miles)		
(A) Total destruction of houses	5	If there be clouds below the point of burst, much of the radiation would be prevented from reaching the ground. However, on a clear day fires and skin burns (on exposed skin) may extend up to a radius of 20 miles, that is, beyond the zone of heavy blast damage.	The gamma rays will give a dose of about 400 roentgens up to a radius of 2 miles. No significant hazard beyond four miles. The radius of hazard due to neutrons would be much less and as such their effect can be ignored.
(B) Irreparable damage to houses	8		
(C) Houses not repairable in short-term (must be vacated for repairs)	13		
(D) Houses repairable in short-term (need not be vacated for repairs)	20		
(E) Light damage such as broken windows	80		

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[4] See for instance, the publication *Operation CUE* (The Atomic Test Program of the FCDA in co-operation with the Atomic Energy Commission, Nevada Test Site, Spring 1955); and also *Nuclear Weapons*, (Manual of Civil Defence: Vol. 1, Pamphlet No. 1), H.M.S.O., 1956.

Radiation Hazard: External and Internal

We shall now pass on to consider the radiological hazard arising from high-yield explosions: It would in general be overwhelmingly large in comparison to blast and heat effects. It is desirable for a proper understanding and appreciation of the new hazard to give a brief account of the effects of ionizing radiation on the human body.* For the sake of convenience we shall consider separately the injury due to (i) deposition of radioactive substances within the body through the process of inhalation, ingestion and/or injection, and (ii) exposure to (penetrating) radiation from sources outside the body. We shall sometimes speak of them as internal and external hazards respectively. In the case of internal hazard, alpha, beta and gamma rays have all to be considered. On the other hand, in the case of external hazard we are really concerned with gamma rays only; alpha and beta rays, on account of their very small range, will be unable to penetrate the body.[5]

We shall first deal with external hazard, and take up the internal hazard later on. In general, in a war using nuclear weapons, the external hazard will be much the more serious of the two.

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* It is interesting to recall that P. Curie was probably the first to demonstrate the harmful effects of radium by voluntarily placing his arm near a radium source for about 10 hours. A scab was formed after 20 days which took more than two months to heal.

[5] If a beta emitter is in direct contact with the skin, the beta rays will penetrate about 1/20 inch into the skin. As these rays cannot reach the hematopoietic system and other sensitive organs of the body, exposure to external beta rays does not result in general radiation injury. However, exposures of 2,000 rad will cause epilation followed by third degree burns which may require extensive skin grafting, but the injury, under proper medical care, is not likely to prove fatal. As alpha rays have a range much smaller than beta rays, an alpha emitter in contact with the body would cause negligible damage.

The mechanism of damage caused to living cells by radiation is still largely and basically obscure; its study is one of the most fundamental and fascinating of contemporary scientific problems. The first step in a series of complex physical, chemical and biochemical events is the ionization of the molecules composing the material of the cells. The act of ionization of a molecule consists in the knocking out, under the impact of the incident radiation, of one or more electrons present in the molecule. As a result of ionization, the molecule usually undergoes disruption. The most remarkable feature of the whole situation is the fact that a cell exposed to radiation dies even when the dose of radiation is no more than what is required to ionize an almost infinitesimal fraction of the total number of molecules present in the cell.

Roentgen, Rad and Rem

In dealing with damage to biological tissues caused by ionizing radiations, it is convenient to define the unit of radiation dose as the quantity of radiation which will produce per unit mass of exposed tissue a fixed number of ionizing acts *i.e.*, ion-pairs. The roentgen (symbol r) is such a unit.[6] We have already used it earlier in the book. A dose of 1 r produces about 1.6×10^{12} ion-pairs in every gram of exposed tissue. This is roughly equivalent to two ionized molecules and about the same number of excited molecules in every cubic micron of the exposed cell. Notice that the statement that a tissue has received a dose of 1 r says nothing at all about the total mass of the exposed tissue that has received this dose.[7] All that it implies is that in every gram of the tissue which has received this dose the number of ion-pairs produced is 1.6×10^{12}.

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[6] The roentgen unit, named after the discoverer of X-rays, was first officially adopted in 1928 at the Second International Congress of Radiology.

[7] Physical quantities are classified into *extensive* and *intensive* quantities. For instance, density and temperature are intensive, and mass and volume are extensive. The radiation dose measured in roentgens is an intensive quantity.

The precise definitions of roentgen and of the other two units[8] used in radiobiology, *viz.*, *rad* and *rem*, are given in Appendix VI. It is enough to state here that 1 r corresponds to an energy absorption of about 93 ergs per gram of tissue. (The rad is defined as exactly 100 ergs per gram of tissue). The following illustrative examples may serve to convey an idea of the magnitude of a roentgen:

(i) A source of one gram of radium produces at one yard from it a dose of 1 r per hour.

(ii) A 60 kilovolt X-ray tube running at 10 milliamperes produces at one yard from it a dose of about 30 r per minute.

(iii) The luminous dial of a wrist-watch (it usually has an activity of about 1 microcurie) produces at one foot from it a dose of about 40 milliroentgens per year.

(iv) In a routine X-ray chest examination a dose of about 0.3 r is received in the chest. In photofluoroscopic chest examination the dose is about 1 r. A chest X-ray from a mobile unit may deliver 2–10 r per exposure.

(v) A person receives a dose of about 10 r in a life-time from background radiation, i.e., cosmic rays and radioactive substances normally present in the air, water and soil.

More examples are given in Chart IV.

The roentgen, unlike the rad and the rem, is applicable to X-rays and gamma rays only. (It is sometimes also used for beta rays). It is not applicable to other ionizing agents such as alpha rays, protons and neutrons, as the *relative biological effectiveness* (RBE) of these radiations is markedly different from that of X-rays and gamma rays.

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[8] The unit rad was first officially adopted at the Seventh International Congress of Radiology in 1953. The unit rem has not yet been officially recognized.

We may consider a typical cell as 5 microns in length and 1 micron in diameter. Such a cell contains about 70 percent water and 27 percent salts and material of molecular weight (M) less than 10^3. The remaining 3 percent of the material consists of about a million protein molecules ($M \sim 10^5$) and a few hundred nucleic-acid-like molecules ($M \sim 10^7$). (A human chromosome which is mainly desoxyribonucleic acid (DNA) is about 2-3 microns long and 0.05-0.1 micron in diameter). A dose of 1,000 roentgens which would be lethal for most cells would produce about 20,000 ion-pairs; and on the basis of molecular weight it is readily seen that this corresponds to only about one percent of nucleic-acid molecules and 0.01 percent of protein molecules undergoing ionization: There is practically no ionization of smaller molecules[9].

It should be observed that unless the dose has been excessively large (thousands of roentgens), an exposed cell is not killed immediately, but continues its activity till it starts to divide—division is a severe test of a cell's vitality — when it either dies in the process of division or gives daughter-cells which are not viable. It is for this reason that tissues composed of dividing cells, e.g., bone marrow, are much more sensitive to radiation than tissues composed of cells which undergo no further division, e.g., the brain. Also for the same reason there is a latent period between the exposure of a person and the clinical expression of radiation sickness.

Radio-sensitivity of Human Tissues

The sensitivity of human tissues to ionizing radiation varies widely. The most sensitive are blood-forming organs and germinal tissues ; the least sensitive are brain and muscle.[10]

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[9] E.C. Pollard, *Statistics and Mathematics in Biology*, edited by O. Kempthorne *et al.*, (Iowa State College Press, 1954), p. 487.

Arranged in the order of decreasing sensitivity, we have lymphatic tissue, germinal epithelium of testis, bone marrow, gastro-intestinal epithelium, ovary, skin, connective tissue, bone, liver, pancreas, kidney, nerve, brain and muscle.[11] Except for the first six or seven, the dose required to inflict any serious damage to the other tissues exceeds the lethal dose for the whole-body-exposure (WBE). The marked sensitivity of the blood-forming organs is of extreme importance in determining the course and nature of radiation sickness. To put the matter crudely, when the exposure to radiation is sufficiently strong (e.g., of the order of 100 r or so) the rate of production of blood cells by the blood-forming organs goes down for a period depending on the severity of the exposure. In consequence, there is a marked fall in the numbers of all the different types of blood cells in circulation, and further the order in time in which the decrease occurs is intimately related to their normal life-span. For instance, the lymphocytes which have a life-span of less than a day are the first to show a noticeable change which takes place within a day or so of the exposure. The erythrocytes (red blood cells) have a life-span of about 120 days, and the fall in their number takes place after about 2 weeks.[12]

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[10] An account of some very interesting work of Soviet scientists on the effect of gamma radiation on the nervous system of animals, on conditioned reflexes etc., is given in *The Proceedings of the International Conference on the Peaceful Uses of Atomic Energy held at Geneva*, 1955, Vol. 11, United Nations, 1956, (referred to hereafter in this book as *Geneva Conference on Atomic Energy*, 1955).

[11] See for instance, *Admiralty Notes on Atomic Energy for Medical Officers*, Chapter 12, H.M.S.O., 1955.

An account of the haematological changes as well as the whole course of acute radiation sickness in persons (two in the USSR and four in the USA) accidentally exposed to radiation is given in *Geneva Conference on Atomic Energy*, 1955, Vol. 11.

[12] Normally about 1 percent of the red blood cells, *i.e.*, roughly 2×10^{11} in number, are disposed of (scavenged) each day as they reach the end of their life-span,

A reasonably detailed account of the changes in the blood picture that take place on exposure to radiation is given in AW (1950).

Permissible Dose

When a person is exposed to ionizing radiation the nature and magnitude of the injury caused to him will depend both on the value of the dose and the rate at which it is received.[13] The same total dose given in a short period in one case and spread over a long period in another case will, in general, produce very different results. (As already mentioned at the beginning of the chapter we are here dealing only with *somatic* effects). It is often assumed (though many will not regard the observational basis as beyond reasonable doubt) that if the dose rate is sufficiently low — below some (finite) threshold value — then a continued exposure even extending over a lifetime will cause no noticeable injury to the exposed individual. The International Commission on Radiological Protection (ICRP) has defined what is termed a *permissible dose* as "a dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. As used here 'appreciable bodily injury' means any bodily injury or effect that a person would regard as being objectionable and/or competent medical authorities would regard as being deleterious to the health and well-being of the individual." Further, *permissible weekly dose* is defined as a dose such that exposure at this weekly rate for an indefinite period will not cause any appreciable bodily injury to a person during his lifetime, and the value recommended by the ICRP is 0.3 r per week for whole-body-exposure.[14] (If only knees and forearms or feet and ankles or head and neck are exposed the permissible dose is given as 1.5 r per week). The Commission has also recommended that in a case of prolonged exposure of large population the permissible dose should be taken as one-tenth of the value accepted for occupational exposures. The USAEC has, however, adopted 3.9 r per year as a permissible dose for non-occupational people, that is, one-fourth of the dose recommended by the ICRP for occupational exposure. If an individual is exposed to radiation at a level which is considered permissible by the ICRP, he would accumulate in one year a total dose of 15 r and as much as 600 r in 40 years. A dose of 600 r seems to be a big dose even if spread over 40 years. If it is received in one day it would in all probability prove lethal.

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[13] We assume a whole-body-exposure (WBE), unless stated to the contrary. When only a part of the body is exposed much larger doses can be tolerated. For instance, if say, only about a square inch of body area is exposed to 400 r no appreciable damage would result, but a WBE of 400 r would have fifty percent chance of causing a fatality.

It appears from some recent work on mammals that even in the case of a very weak dose some irretrievable or irreversible damage is always caused to the exposed individual. If this result is substantiated by further work it would mean that there is no threshold even for somatic damage. One reason for the hypothesis that there is always some irreversible injury associated with radiation exposure, no matter how small, is the fact brought out in some recent experiments on mammals that radiation exposure has a cumulative effect in shortening the life-span.[15] *The shortening of the life-span is about one percent for a dose of 100* r. (Thus a dose of 600 r which a person can accumulate in 40 years at an exposure level permitted by the ICRP recommendations would cut down his life by about 6 percent).

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[14] "Recommendations of the International Commission on Radiological Protection (Revised December 1, 1954)", *British Journal of Radiology, Supplement No. 6*, 1955.

[15] H.A. Blair, *Geneva Conference on Atomic Energy*, 1955, Vol. 11;

It is worth noting, as March[16] found, that deaths due to leukemia amongst radiologists in the US from 1928 to 1948 were 4.7 percent as against 0.5 percent in non-radiologist physicians. It has also been found that radiologists as compared to non-radiologists have on an average a life-span shorter by about 5 years. A detailed study[17] of the survivors of the Hiroshima bombing has shown that the deaths due to leukemia in the period 1948-50 were three to five times above the normal value for Japan.

All available experimental evidence shows that ionizing radiation has no beneficial effects on the exposed cells. (The relief that a cancer patient gets from radiation exposure is due to the fact that the rapidly multiplying cancer cells being much more sensitive to radiation suffer greater damage than normal cells of the body). The situation is best summarized in the following observations of the ICRP: "While the values proposed for maximum permissible exposure are such as to involve a risk that is small compared to the other hazards of life, nevertheless in view of the unsatisfactory nature of much of the evidence on which our judgments must be based, coupled with the knowledge that certain radiation effects are irreversible and cumulative, *it is strongly recommended that every effort be made to reduce exposures to all types of ionizing radiations to the lowest possible level.*"[18] There can hardly be any doubt that the exposure levels permitted by the ICRP are on the high side, and particularly so when genetic effects, described in the next chapter, are considered. It is expected that the ICRP values would be revised downwards in the near future.

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[16] H.C. March, " Leukemia in Radiologists in a 20 Year Period", *American Journal of Medical Science*, **220,** 282 (1950).

[17] Nobuo Kusano (Chief Editor), *Atomic Bomb Injuries,* Tokyo, 1953.

[18] In this connection the following observations of Marcovich are significant: " The frequency of induced cancers increases with the dose, but so does the latency period which separates the moment

50 *Percent Lethal Dose*

So far we have been dealing with relatively low dose rates extending over long periods. We now turn to the effects of large doses delivered in a short period. It is necessary to have some idea of the effects of large doses in order to appreciate the serious hazard arising from exposure of persons to local fallout from nuclear explosions. Work has been done on many animals — from insects to monkeys — to determine what is termed the 50 percent lethal dose (referred to as LD-50). This is defined as the dose which, on an average, would cause lethality in 50 percent of the exposed individuals. Experiments have shown that LD-50 is fairly reproducible. Table IX gives LD-50 values in a few typical cases[19].

(It may be of interest to observe that micro-organisms are much more resistant to ionizing radiation than mammals. This, in a way, is to be expected considering the much greater complexity of the life processes in mammals. The lethal dose for insects is about ten times larger than for mammals, and for micro-organisms it is about hundred times larger still. Ionizing radiation is being used, though not as yet on a commercial scale, for sterilization and preservation of food. The doses required may be as high as a few million rads).

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of irradiation from the appearance of the cancer. Thus, we may conclude to the existence of an action threshold without denying it. The very nature of such a threshold is difficult to conceive, since the factors of carcinogenesis are always many, and the interactions very complicated. Nevertheless, it seems reasonable to assume that, all conditions being equal, ionizing radiations give us another means of inducing cancer, which one may not rule out even at the smallest doses." (*Geneva Conference on Atomic Energy*, 1955, Vol. 11).

[19] If LD-95 and LD-5 denote respectively dose values for 95 percent and 5 percent deaths, then the ratio of LD-95 to LD-5 is usually less than 2 for most mammals, but possibly greater than 3 for man.

TABLE IX

LD-50 dose for various mammals

Mammal	Gamma dose in roentgens for 50 percent lethality
Guinea pig	200
Dog	300
Monkey	500
Rat	600
Rabbit	800

Obviously it is not possible to determine directly the value of LD-50 for man. However, on the basis of considerable clinical experience extending over several decades in the treatment of patients with X-rays and radioactive sources, and making use of the unfortunate experience of Hiroshima and Nagasaki, and the accidental exposure of individuals to acute doses,[20] it is generally assumed that LD-50 is 400-500 r. We shall take it here as 400 r. A dose of 800 r will kill over 95 percent of exposed individuals. In general, death would not occur immediately on exposure but will take a few weeks. It will require much heavier doses (about 10-100 times the LD-50 value) to cause immediate death.[21]

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[20] " Instances of serious or even fatal injury as a result of overexposure to X-radiation continue to occur. Doctors not trained in radiology who perform roentgen diagnostic procedures are particularly apt to suffer severe injury. This appears to be the result of carelessness, indifference, or ignorance of the dangers of excessive exposure. Many physicians are not aware of the methods available to reduce the amounts of radiation to which they may be subjected.....The incidence of leukemia in radiologists and others exposed to radiation is higher than in other physicians. Gonadal effects vary from impairment of fertility to genetic alterations. The first generation offspring of radiologists and others exposed to irradiation show a statistically significant higher percentage of congenital malformations. Second and future generation incidence should be higher, predicted on the basis of animal experiments. The

A person receiving a dose of 400 r over the whole body will absorb about 200 ft lb of energy. It is a pure coincidence that this energy is comparable to the minimum energy which a rifle bullet must spend in inflicting a mortal wound. Incidentally, the energy imparted in a hand-shake is comparable to a whole-body-exposure of a few roentgens. However, 400 hand-shakes cannot undo or do the effect of 400 r. Hand-shakes do not ionize atoms; but gamma rays do and thus dislocate the basic processes taking place in living cells of the body, resulting in fatal consequences. The probable effects arising from different levels of exposure are summarized in Table X, which is reproduced from *Nuclear Weapons*, (Manual of Civil Defence: Vol 1, Pamphlet No. 1), H.M.S.O., 1956.

The effects given in Table X are for short duration (immediate) exposure. The same dose spread over a relatively long duration has less severe effects. For instance an acute dose of 500 r is roughly twice as effective as the same dose spread over a period of one day. It has been suggested that a permissible dose in wartime may be 25 r for a single exposure of a few hours. An exposure of twice this value would be permissible if the dose is spread over two or three days.

It may be noted that in the case of radiation sickness, vomiting is a common symptom and its onset can be taken as a rough measure of the severity of exposure.

It should be noted that radiation exposure has a marked effect on fertility. In this case it is only the

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' maximum permissible dose ' of 300 mr per week is but a guide for safe procedure, and it is wise to adopt the principle that excess radiation comprises any radiation which can be avoided." (Max Ritvo *et al.*, " Radiation Hazards to Non-radiologists participating in X-ray Examination", *The Journal of the American Medical Association*, **160,** 4 (1956)).

[21] K.C. Brace and H.L. Andrews, " Early Radiation Death", *Geneva Conference on Atomic Energy*, 1955, Vol. 11.

TABLE X

Probable effects on people of a single exposure to gamma radiation

(Data provided by the Medical Research Council, UK)

Single dose: range in roentgens	Mortality at 24 hours	Mortality at 6 weeks	Number incapacitated within 24 hours	Probable time of unfitness for any duties of those affected
0—25	0	0	Negligible	2-3 days
25—75	0	0	A few	2-3 days
75—100	0	Less than 0.1%	Up to half	1-2 weeks
100—150	0	Less than 0.5%	At least half	About 3 weeks
150—200	0	Up to 5%	At least three-quarters	Not less than 3 weeks ; some very ill
200—400	Unlikely to be any	About a third	Probably all	Not less than 3 months
400—600	Perhaps a few	About half	Probably all	Not less than 3 months
over 800	Likely to be some	Almost all	Probably all	—

dose which is received by the gonads that is relevant. The fertility during a month or so following the exposure is not appreciably affected but, depending upon the strength of the dose, there follows a period of reduced fertility which may last a few months or more.[22] If the dose delivered to the gonads is sufficiently large, say 1,000 r, permanent sterility may result. As Loutit[23] has observed : "Following large single doses of radiation to the whole body sterility rapidly ensues. Developing ova and developing sperm are extremely susceptible though mature sperm are much less so. Therapeutically a dose of a few hundred roentgens to the ovary is used for producing a premature menopause. Larger doses than this are usually required completely to sterilize a male, though this is not as far as I am aware a therapeutic procedure. The ovary once its developing eggs are destroyed cannot produce new ones. The testis can on the other hand recover in many cases."

The Nineteenth Semiannual Report of the USAEC, January 1956, gives two instances of another possible insidious effect of exposure to moderate doses of ionizing radiation :

"Experiments with monkeys at the Johns Hopkins University School of Public Health indicate that moderately incapacitating doses of ionizing radiation frequently reactivate latent epidemic typhus infections in animals which had completely recovered from the disease several months prior to the irradiations. Heavy doses of cortisone may also lead to reactivation of these dormant infections. This suggests the possibility of a public health hazard, which might complicate the aftermath of a very heavy exposure of densely populated areas to nuclear radiation.

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[22] It may be mentioned that temporary sterility was induced in the fishermen of *Fukuryu Maru*. They received a dose of a few hundred roentgens from the fallout of March 1, 1954 test explosion.

[23] J.F. Loutit, "The Experimental Animal for Study of the Biological Effects of Radiation", *Geneva Conference on Atomic Energy*, 1955, Vol. 11.

"Evidence of a previous typhus infection was found in about 1/3 of a large group of Baltimoreans who emigrated from Eastern Europe some decades ago. Among those persons there has been a small number of cases of apparent reactivation of the disease following incidental treatment with cortisone or radiation."

Modification of Radiation Response in Animals

At this stage it is important to observe that in experimental animals (mice) it has been possible to modify the value of LD-50 by artificial means.[24] It has been known for some time that radiation sensitivity of cells to X- and gamma rays depends on oxygen tension, that is, the concentration of oxygen present in the cells. The oxygen-effect is much less for neutrons and practically absent for alpha rays. The reason for this lies in the specific ionization being very different for these radiations. A decrease in the oxygen tension below normal brings about a proportionate decrease in radiation sensitivity, whereas an increase in oxygen tension has little effect.[25] A similar effect takes place for simple inorganic systems such as the radiation-induced oxidation of ferrous sulphate in water. The presence of oxygen can increase, by a factor of four, the yield of the oxidation-reaction. In biological systems water molecules are present in great abundance, and these under the action of ionizing radiation break up into H and OH radicals. In the presence of oxygen, H combines with O_2 to form active oxidizing radicals such as HO_2. Thus it may be said that the role of O_2 is to mobilize H also for oxidative purposes.[26]

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[24] For a recent review of the subject see A. Hollaender and R.F. Kimball, *Nature*, **177,** 726 (1956).

[25] As a possible consequence of the 'oxygen-effect' is the observed fact that opacity (cataract) of the eye lens is much more rapidly induced by fast neutrons than by X- or gamma rays. The eye lens has no blood vessels. It gets its oxygen supply through a process of slow diffusion, and as such the oxygen concentration in it is much less than in other tissues of the body. On account of the reduced oxygen tension the radio-sensitivity of the eye lens is considerably reduced for gamma rays. This does not apply to fast neutrons (which cause ionization through recoil protons) as these and other particles with high specific ionization show no decrease in radio-sensitivity under reduced oxygen tension.

The increase in radiation resistance under reduced oxygen tension is strikingly demonstrated in experiments on mice. It has been found that placing the mice in an atmosphere of 5 to 7 percent of oxygen during exposure almost doubles the LD-50 value. This technique is obviously not applicable to men as breathing under a reduced oxygen atmosphere would lead to serious consequences. However, there is another line of approach which seems very hopeful. Certain chemicals such as cysteine and cysteamine when administered to mice in optimum quantities almost double the LD-50. The mode of action is not yet understood: It appears that in some cases they directly react with the oxidizing radicals, the effect being the same as if the oxygen tension were reduced. The above chemicals cannot be given to men in the required quantities because of their toxicity. It is possible, however, that other less toxic protective substances may be discovered in the near future.

What has been said so far relates to *pre-exposure* treatment and is intended to strengthen the organism's mechanism for protection against radiation. Procedures have also been discovered for mitigating the effects of exposure. The most effective *post-radiation* treatment so far worked out for mice consists in the transplantation or injection of spleen and of bone marrow from unexposed subjects. The general conclusion which emerges from all this work is that it is possible to modify the physiological damage caused by ionizing radiation in mammals. Work is in progress to extend this to men. However, it seems unlikely, on general arguments, that any modification so introduced would do very much more than double the LD value.[27]

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[26] L.H. Gray, " Some Characteristics of Biological Damage Induced by Ionizing Radiation ", *Radiation Research*, **1**, 189 (1954).

Radiological Hazard due to Multi-megaton Explosions

After this somewhat long digression on radiation response, we can now consider the radiological hazards arising from multi-megaton nuclear explosions. As already remarked at the beginning of the chapter, we shall deal here only with somatic effects, that is, injury caused to the exposed individual: The genetic effects are described in the following chapter.

The radiological hazard of a nuclear explosion is due to the radioactive substances resulting from the explosion.[28] It is convenient for our purpose to distinguish between

(*i*) radioactivity of the fission products, and plutonium and uranium left over unfissioned at the end of the explosion, and

(*ii*) radioactivity induced in the surroundings (atmosphere and the earth's surface in the vicinity of the explosion) by the absorption of neutrons liberated in the explosion.

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[27] While the mechanism of radiation damage is not clear, it is likely that part of the damage is, crudely speaking, physical in origin, *e.g.*, breakage or aberration of chromosomes under the direct impact of the incident particle, and that a part is chemical and biochemical in nature. It seems that whereas the chemical damage could be reduced by artificially altering the chemical environment of the cell, it seems very unlikely that the physical damage could be lessened to any marked degree.

[28] We have earlier considered the effects of *initial nuclear radiation* (gamma rays and neutrons). This is defined as the radiation emitted in the first minute or so of the explosion, that is, before the bomb cloud has spread out to any appreciable extent. The radius of damage (to personnel) for initial nuclear radiation is considerably less than the radius of destruction due to blast and heat.

(Under (*ii*) we should also include the neutron-induced activity in the material of the bomb cloud). For an all-fusion explosion component (*i*) is practically absent. For a fission explosion both (*i*) and (*ii*) are present, but the contribution of induced radioactivity is relatively insignificant, being roughly of the order of 1 percent of the activity of fission products. Also the unfissioned plutonium and uranium constitute a very minor internal hazard when compared to the serious external hazard due to the fallout to be described presently.

Neutron-induced Radioactivity

At this stage it would be appropriate to say a few words about neutron-induced radioactivity of nuclear explosions. A nominal high-yield fission explosion liberates about 10 kilograms of neutrons (Table XII). However, it is only a small fraction of these neutrons which can get out of the bomb cloud : We shall assume a figure of 10 percent. A detailed study of neutron-induced activity has been made both for an underwater and an underground burst[29]. In the case of an air burst it is safe to assume that all the neutrons escaping from the bomb cloud will be absorbed by the nitrogen in the atmosphere producing radioactive carbon 14. In an underwater burst most of the neutrons are absorbed by hydrogen to form the stable heavy hydrogen. The elements sodium and manganese which are present in water as impurities make the largest contribution to the neutron-induced activity after a few hours from detonation. The same elements also make a major contribution to induced activity for an underground explosion. In Table XI values for the total neutron-induced activity are given for different times from the instant of detonation[29].

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[29] C.E. Mandeville, *Journal of the Franklin Institute*, **252,** 297(1951).

TABLE XI

Neutron-induced activity

Time from detonation	Neutron-induced activity in *curies* due to nominal high-yield fission bomb		
	Air burst	Underwater burst (fresh water)	Underground burst
0	6.4×10^4	1.4×10^9	2.8×10^{12}
1 hour	6.4×10^4	5.0×10^5	1.2×10^{11}
1 day	6.4×10^4	6.0×10^1	2.8×10^9
1 week	6.4×10^4	$< 4\times10^2$	4.0×10^6

Fission and Fusion Explosions

In the case of an all-fusion explosion of energy equivalent to 20 million tons of TNT, the induced activity would be substantially more than that given in Table XI. An upper limit for the activity may be obtained by multiplying the figures by a factor ten. Further, the end-products of a fusion explosion are mostly stable nuclei, and it will not be unreasonable to assume that their contribution to the radiological hazard of the explosion is relatively negligible.

A glance at Tables XI and XII shows that the activity of the fission products is *far larger* than the neutron-induced activity. This holds provided the duration from the instant of explosion is not unduly long, *i.e.*, not more than a few years; but by then the activity would be negligible anyway. (A possible internal hazard arising from carbon 14 is discussed later in this chapter).

The foregoing discussion leads us to the general conclusion that firstly the radiological hazard of an all-fusion explosion is relatively negligible compared to that of a fission explosion of the same energy, and secondly for a fission explosion the hazard is almost all contributed by the fission products.

TABLE XII

Nominal high-yield fission explosion

Energy equivalent to	20 million tons of TNT $= 8.4\times10^{23}$ erg
Released in explosion:	
(*i*) Fission products	= 1,000 kilogram (2,200 lb)
(*ii*) Neutrons	= 10 kilogram (22 lb)
Gamma activity in curie* of fission products at *t* hours from detonation	$= \dfrac{6.0\times10^{12}}{t^{1.2}}$ $= 8.2\times10^{14}$ at end of minute $= 6.0\times10^{12}$ at end of 1 hour $= 1.3\times10^{11}$ at end of 1 day $= 1.3\times10^{10}$ at end of 1 week
Activity of strontium 90 contained in fission products	$= 2.8\times10^{6}$ curie (14 millicurie per square mile of earth's surface)
Gamma activity of 10,000 curie per square mile gives (near the surface) dose rate	= 1 r per day

Fallout: *Local and Global*

A high-yield fission explosion produces, as we have seen, vast quantities of radioactive fission products. The extent and the magnitude of the resulting hazard depend on how and where these active products of the explosion are deposited. This leads us to a consideration of the types of bursts.

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* 1 curie $= 3.7\times10^{10}$ disintegrations per second.

In the preceding chapter we have given an account of the effects of different types of bursts for a nominal A-bomb. We shall now consider (*i*) air burst and (*ii*) ground or surface burst for a nominal high-yield fission bomb.[30] Take first the air burst.

In an air burst the fire ball does not touch the earth's surface — note that the diameter of the fire ball would be about 3 miles or so — and as such, relatively speaking, little outside material can get into it. In consequence, the fission products, under the terrific force and heat of the explosion, are dispersed into extremely fine particles and the volatile components reduced to a gaseous state. They are carried into the stratosphere and being in an extremely fine state (from less than a micron to a few microns in diameter) stay there for years, maybe decades. They only gradually return to earth. During the process they are widely scattered by the winds and settle down more or less uniformly over the entire surface of the globe. This is termed *global fallout.*

The situation is quite different for a ground or a surface burst. In this case a substantial part of the fire ball comes in close contact with the earth, producing a gigantic crater a mile or more in diameter and projecting into the fire ball about 10-100 million tons of vaporized earth, dust and debris.[31] The fire ball rapidly moves upward expanding and cooling as it does. It reaches a diameter of over three miles. Strong upward air currents follow the rapidly rising ball carrying with them more dust and debris. After a few minutes the explosion cloud reaches the tropopause at a height of 30-40 thousand feet. It meets here a temperature-inversion in the atmosphere which considerably slows down the upward motion. The cloud expands laterally into a 'mushroom' or 'cauliflower' about 100 miles in diameter placed on the top of a stem of diameter about the same as that of the fire ball (3 miles). The central portion of the cloud (head of the stem) still continues to push upwards, reaching 80-90 thousand feet in about 10 minutes, but because of the marked increase in the temperature with height in the higher levels of the stratosphere, it does not go much beyond 100,000 feet (20 miles). The fission products condense and collect on the very abundant dust particles present in the explosion cloud,

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[30] In the preceding chapter on A-bomb a reference was made to underground burst. A deep underground multi-megaton explosion would generate energy comparable to a big earthquake and the destruction wrought would also be of the same nature and magnitude. It should be noted that, unlike the case of an underground explosion, for a ground or surface explosion the energy going into seismic waves is only a small fraction of the total energy. Thus for the Oppau explosion of September 21, 1921, caused by the detonation of about 4,000 tons of ammonium nitrate, it is estimated that 0.1 percent of the total energy was transformed into seismic waves. For an underground, as also for a deep underwater explosion, the fission products would be unable to escape into the atmosphere in any appreciable amount : The fallout would be confined to the immediate vicinity of the explosion site (i. e., crater for an underground burst) and the radiological hazard would therefore be relatively less important than the destruction caused by blast.

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[31] The November 1952, 5 megaton explosion at Eniwetok (Operation IVY) wiped out a small island (Elugelab), the crater being a mile in diameter and 170 feet deep. The volume of the crater was about 1/80 cubic mile, representing 50 million tons of earth. The fire ball reached a diameter of 3½ miles and the stem went up to 25 miles in the stratosphere. The mushroom cloud formed at about 10 miles level was over 100 miles in extent.

The crater diameter referred to above roughly agrees with the usual formula for ordinary explosives:

$$\text{crater diameter (feet)} = 2 \times (\text{explosion energy in lb of TNT})^{\frac{1}{3}}$$

In considering megatons explosions it is interesting to recall the great volcanic eruption of Krakatoa in August 1883 which ejected into the atmosphere lava and ash variously estimated as between 100 million tons and 20,000 million tons. It has been estimated that about one-third of the material fell within 30 mile radius, another one-third within 2,000 miles, the rest remained suspended for about three years.

and sooner or later this huge quantity of contaminated dust and debris returns to the earth.

We just spoke of the tropopause. The region of the atmosphere above the tropopause is called stratosphere. The height of the tropopause is about 10 miles in tropical latitudes and 5 miles in temperate latitudes. The phenomena of weather, *e.g.*, winds and storms, clouds and rain, all take place in the troposphere. The stratosphere is a region of calm, free from winds and turbulence. The temperature in the atmosphere (leaving aside the lowermost regions) decreases (in general) with increasing height till the tropopause is reached. Near the tropopause the temperature, instead of decreasing with increasing height, shows a rapid increase. This is called temperature-inversion. Some distance above the tropopause the temperature attains a value of about – 50 deg.C and remains constant till about 20 miles or so when it again begins to rise. The effect of the temperature-inversion at the tropopause is to retard the motion of the ascending current of air. The result is that unless a convection current is exceptionally strong it is unable to penetrate into the stratosphere. The dust and dirt that goes up with a convection current is all brought to rest at the tropopause. Sooner or later these particles of dust again return to the earth. The rate of fall of a particle in still-air depends on its size. It varies as the square root of the diameter for particles which are relatively large (a millimeter or more). For smaller particles (less than about a millimeter) Stokes' law holds and the rate of fall is proportional to the square of the diameter ; a 100 micron particle will take about four hours to fall through 40,000 feet whereas a 10 micron particle will take about two weeks. In fact, for particles smaller than about 5 to 10 microns in diameter the rate of settling down under gravity is altogether negligible. There are, however, other processes in the atmosphere which bring such particles back to the earth's surface. The most effective of such mechanisms—and it applies to small as well as large particles—is rain. Even 0.1 inch of rainfall is enough to clear the atmosphere practically of all its dust. This phenomenon is sometimes spoken of as wash-out.[32]

It is interesting to observe that the size distribution of particles in the Alamogordo test explosion ('Trinity' test) was found to be roughly the same as for the dust raised over the Sahara desert. Table XIII [reproduced from AW (1950)]—based on the assumption that the size distribution is the same as for the dust over the Sahara Desert — gives an indication of the size of particles in an atomic cloud. The height of the cloud is assumed to be 40,000 feet. The figures in the last column add to about 50 percent; the other 50 percent is due to the very small particles which remain in the atmosphere for a very long time.

TABLE XIII

Proportion of active material deposited from atomic cloud

Period (minutes)	Diameter of dust particles (microns)	Proportion deposited (percent)
0 — 22	840	3·8
22 — 42	840—250	12·6
42 — 117	250—150	14·5
117 — 480	150—75	18·1

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[32] In this connection it is interesting to observe that recent work on the coalescence of water droplets has shown that the flow field around a falling drop is such that it sucks in its way dust particles or other drops that may be present. This scavenging effect extends over an area of about 100 times the cross section of the drop and up to a distance of 40 diameters behind it. It is a very effective mechanism in the formation of large drops from small drops.

An interesting account of the meteorology relevant to nuclear explosions is given in *Meteorology and Atomic Energy*, USAEC, 1955.

The above brief description of the structure of the atmosphere is necessary for an understanding of the different types of fallout from nuclear explosions. In the case of a high-yield explosion, because of the terrific force and heat released, a considerable portion (the central part) of the rapidly ascending explosion cloud will be able to penetrate the tropopause and go to considerable heights into the stratosphere. The relatively large particles will soon return to the tropopause but small particles, about a micron or so in diameter, will stay in the stratosphere for a long time, on an average about 10 years. The portion of the fission products that goes into the stratosphere will return to the earth at an extremely slow rate. As the process of diffusion and mixing will operate in this case for a relatively long time, the fallout will be more or less at the same rate over the entire surface of the globe. This is called *global fallout*.[33]

We now come to the portion of the explosion cloud that remains in the troposphere. The comparatively large particles, 10-500 microns, return to the earth in a few hours to a few days. This constitutes the *local fallout*. The smaller particles stay in the troposphere for a couple of weeks and during this time the radioactive cloud travels (generally from West to East, due possibly to jet-streams) two or three times round the earth. This gives rise to fallout along a fairly wide belt round the earth roughly running parallel to the latitude of the explosion site. We shall speak of it as *annular* (*semi-global*) *fallout*. It is more intense near the explosion site than in regions remote from it. The dust particles in the troposphere stay on, on an average, for a week or two. In temperate latitudes they are usually brought down by rain which provides, as we have said earlier, a most effective mechanism of wash-out.

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[33] Libby, on the basis of actual measurements of global fallout from 'high-yield test explosions', has suggested that roughly 50 percent of the fission products go into this type of fallout.

What we have said so far applies to a high-yield explosion. For explosions in the kilotons range, *e.g.*, nominal A-bomb, the explosion cloud will be unable to rise above the tropopause in any appreciable measure. The fallout in this case, therfore, will be only local and annular, and not global. The types of fallout and a qualitative indication of the relative distribution of fission products are given in Table XIV.

In a war with high-yield fission weapons the most serious hazard, as we shall see presently, is from local fallout.[34]

TABLE XIV

Fallout from nuclear explosions

	Local	Annular (semi-global)	Global
Portion of earth's surface over which fallout occurs	Vicinity of explosion	Belt round the earth in the latitude of explosion site	All over the earth
Duration of fallout	A few hours to a few days	A few weeks	About 10 years
Relative distribution of fallout (qualitative indication):			
(*a*) Air burst	Small ($\sim$ 1/10)	1/3	2/3
(*b*) Ground burst (Kilotons explosions)	2/3	1/3	Negligible
(*c*) Ground burst (Megatons explosions)	1/4	1/4	1/2

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[34] The situation is of course quite different with regard to peace-time nuclear tests. These tests are conducted in isolated atolls and other places far away from population centres, and by taking stringent precautions the hazard of local fallout is almost completely eliminated. We are left, however, with the effects of global and annular fallout. These are described later in this chapter as well as in the one that follows.

The pattern of local fallout (for a surface burst) depends on a variety of complex factors, the most important being the particle-size distribution in the explosion cloud and the prevailing meteorological conditions.

The particle-size distribution will depend to some extent on the degree of contact of the fire ball with the surface of the earth and on the nature of the surface. The quantity of material sucked into the fire ball and also the process of fallout would, in many ways, be different for a burst over water and for a burst over ground. Again, the nature of the surface coming into contact with the fire ball, *e.g.*, whether water, coral, granite or sand, determines whether the fallout will be largely water-soluble or insoluble. This is of some importance from the point of view of direct assimilation by plants of fallout material coming into contact with green foliage. (Direct absorption through the skin into an animal body also depends on the water-solubility of the fallout). From the point of view of decontamination measures of areas or persons subjected to fallout, it makes a difference whether the fallout is soluble in water or not.

The most important meteorological factor which is relevant in determining the pattern and extent of local fallout is the direction and intensity of prevailing winds. It is extremely important to note that it is not the wind at the surface which determines the pattern, but the wind-structure from above a few thousand feet to about 100,000 feet or so. As the entire wind-structure is involved, and as winds are constantly changing in strength and direction, it becomes very difficult to make any long-range or even short-range prediction of the pattern. Under average conditions the area of hazard from local fallout is directly proportional to the total quantity of fission products generated in the explosion, or, in other words, to the explosion energy itself. The radiological damage inflicted by a nominal high-yield fission bomb would therefore be a *thousand* times more than that of a nominal A-bomb. Notice that the area of blast destruction for a nominal high-yield bomb is only a *hundred* times the area of destruction for a nominal A-bomb. The high-yield fission weapon is thus primarily a radiological weapon.

Area of Local Fallout

A nominal high-yield fission explosion releases 1,000 kilograms of fission products. We shall suppose, as a basis for calculation, that one-fourth of the fission products go into the local fallout, and that on an average it takes 8 hours for the precipitation to take place. If R denotes the dose received by a person (standing in open in the area A of fallout) exposed to gamma radiation from the fallout for a period beginning at 8 hours from detonation to $(8+t)$ hours, then the product of A and R for different values of t is given in Table XV. These values can be readily obtained from Charts I (a) and I (b).

TABLE XV

t	RA (roentgen-square-mile)* 10^6
0	0
1 day	5·0
2 day	6·7
1 week	9·6
1 month	12·3
Eternity	20·8

The dose values given in the above table are for a person standing in the open in the area of fallout. A person sheltered in a house will receive a reduced dose on account of the absorption of gamma rays in the material of walls *etc.* The shielding factor, sometimes also called the dose-reduction factor, is defined as the ratio of the dose for a " protected " person to the dose received in the open, other conditions remaining the same. The values of the shielding factor for a few typical situations are given in Table XVI.

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* The area A is in square miles and the dose R is in roentgens.

TABLE XVI

	Shielding factor[35]
Behind 3 in. concrete (or equivalent in brickwork or earth) ..	1/2
Behind 6 in. concrete (or equivalent in brickwork or earth) ..	1/4
Behind 9 in. concrete (or equivalent in brickwork or earth) ..	1/10
Behind 12 in. concrete (or equivalent in brickwork or earth) ..	1/20
In middle of ground floor of two-storey house in built-up area (distance and shielding) ..	1/40
In slit trench with 1 ft of earth cover overhead ..	1/100
In basement shelter ..	1/200-1/300
In slit trench with 3 ft of earth cover overhead ..	1/(300 +)

(1 ft of concrete = 15 in. of brickwork or 18 in. of earth)

We thus see from Table XV that if the area covered by the fallout is about 10,000 square miles (which is a reasonable figure) the average dose received by an exposed person for a duration of 2 days is about 670 r. If the area of fallout is assumed ten times larger, the dose would be one-tenth of the above value. Even this latter figure represents a serious dose, and more so when we remember that this is an average to which everyone in a huge area of 100,000 square miles would be exposed.* We may take 100,000 square miles as probably the upper limit for the area of radiological hazard arising from a nominal high-yield bomb. The actual area of serious hazard from local fallout will depend, as we have said earlier, on meteorological conditions and many other factors, but in a 'normal' strategic attack it is more likely to be 100,000 rather than 10,000 square miles.

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[35] *Nuclear Weapons*, (Manual of Civil Defence : Vol. 1, Pamphlet No. 1), H.M.S.O., 1955.

From what has been said above it is apparent that a high-yield fission bomb is primarily a radiological weapon. The blast effect of a single megatons weapon is enough to destroy the very largest of the cities; its radiological effect is enough to devastate an area as large as that of some of the largest states in our country. 100,000 square miles is not a small area; it is in fact only somewhat less than 1/500th part of the total land surface of the earth.

High-yield Fission Explosion, March 1, 1954

We now come to the March 1, 1954 test explosion of a ' very large thermonuclear device ' — so the USAEC described it at the time—exploded on a coral island in Bikini Atoll (in the heart of the Pacific Ocean). The energy released was equivalent to about 15 million tons of TNT and was practically all obtained from the fission of uranium 238. The accidental exposure of the Japanese fishing boat *Fukuryu Maru* to the local fallout from the explosion has already been referred to in Chapter II. The boat was about 90 miles to the east of the explosion site.†

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* The dose of about 70 r would have serious genetic effects (see Chapter VI).

† The ' warning area ' was defined by N 10° 15′—12° 45′, E 160° 35′—166° 16′, enclosing an area of roughly 50,000 square miles. The position of No. 5 *Fukuryu Maru*, at the time of the explosion (3-40 A.M.) was N 11° 53′, E 166° 58′, about 80-90 miles east of Bikini. For subsequent tests (March 19 to May 22) the warning area was enlarged to roughly a semi-circle of radius 450 miles, that is, an area of about 300,000 square miles.

A greyish-white ash (fallout) began to fall on the boat about 3½ hours after the explosion, and the 'shower' continued for 4 hours. The amount of ash deposited on the boat was estimated to be roughly of the order of 50 grams per square meter of the boat's surface. (This was done by experimentally reproducing the 'fallout' using pulverised coral reef—in the presence of the exposed fishermen as witnesses). Some of the larger granules in the ash were about 0.1 to 0.5 millimeter in size. These were found on microscopic examination to consist of fine particles (cubic and spindle shaped) of size comparable to a micron. Electron diffraction studies of the *Fukuryu Maru* dust by the Japanese investigators indicated that under the heat of the explosion the coral reef first evaporated and later, on cooling, recrystallized into calcite with the inclusion or absorption of radioactive nuclides produced in the explosion. It may also be noted that measurements of the polarization of skylight in Tokyo (in August 1954) showed the presence, in the upper atmosphere, of dust particles of about 0.8 to 1 micron.[36]

The measurement of the rate of decay of radioactivity of the ash collected from *Fukuryu Maru* indicated that at the time the ash fell on the boat its activity was about 1 curie per gram of the ash. As 1 gram of pure fission products has an activity of about 2 million curies at about 3 hours from detonation,[37] it follows that the fission products (weighing about 1,000 kilograms or 1 ton) suffered a dilution with about 2 million tons of inactive coral dust. The total quantity of dust and debris sucked into the fire ball would probably be of the order of 10-100 million tons, as most of it, instead of mixing with fission products, would return to earth in the form of large aggregates in the immediate vicinity of the explosion.

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[36] See Y. Nishiwaki, *Atomic Scientists Journal*, **4,** 279 (1955), for an account of the Japanese observations on effects of test explosions, in particular the fallout deposited on *Fukuryu Maru*.

[37] See Chart I (a).

We have just said that the intensity of fallout of *Fukuryu Maru* was about 50 grams per square meter. This would mean a radioactivity of 50 curies per square meter at the time the ash fell on the boat and would correspond (say, for an exposure of about 2 weeks) to a total dose of about 6,000 r for an unprotected person. This is a terrific dose and would be 100 percent lethal. The estimated dose of 6,000 r is very much on the high side as it does not take account of the washing away of the ash from the boat. It is also likely that the assumed intensity of fallout is larger than the actual value by a factor of about 3. Further, the fishermen were not in the open but sheltered to some extent, and as such the dose received by them would be substantially reduced. The total dose received by them—they were in the boat for 13 days—could not have exceeded a few hundred roentgens as all the 23 fishermen (with the possible exception of one[38]) survived the effects of the exposure.

A reference may also be made here to the accidental exposure of 28 American Servicemen and 239 Marshalles to the fallout from the March 1, 1954, explosion. The whole-body-dose received by them varied from about 15 to 175 r. A dose of 175 r was received by a group of 64 Marshalles. There was no fatality; but, beginning about two weeks after exposure, 90 percent of the cases developed skin lesions and epilation. At the end of one year the people were found to be generally in good health.[39, 40]

The first official announcement about the pattern of local fallout for the March 1, 1954, explosion was made by the USAEC on February 15, 1955, and this is the only test explosion about which such information has been released. The fallout pattern is graphically depicted in Chart III which is based on the data given in the USAEC report referred to above. The pattern is cigar-shaped (*i.e.*, oval) and the area of hazard is about 7,000 square miles. A person standing in the open in this area would, on an average, receive a dose of roughly 1,000 r for an exposure of 36 hours commencing at 8 hours from detonation. The radii of the areas of destruction by blast and heat and the length of the fallout (which would be oval) are diagrammatically shown in Chart II. The corresponding values for a nominal A-bomb are also given for comparison. There is one thing which stands out clearly above everything else: A high-yield fission weapon is essentially a radiological weapon. The area of serious hazard from local fallout is terrifically large. For the March 1954 explosion it was about 7,000 square miles. However, as already emphasized earlier, the shape and area of local fallout are strongly dependent on the prevailing meteorological conditions and, in particular, on the wind velocities from ground level to about 100,000 feet. As a crude supposition if we assume that it takes about 8 hours for particles constituting local fallout to descend to earth from the upper atmosphere—a particle of size 0.1 mm would take about 8 hours to fall through 70,000 feet—then an average wind speed of 30 miles per hour would carry the particle downwind to a distance of 240 miles. This is comparable to what was observed in the March 1954 explosion. If the time of attack is so chosen that the wind speeds are relatively high—note again that one is not concerned with the wind velocity near the ground, but the average of wind velocities at heights from 10,000 feet or so to about 100,000 feet—the area of hazard would be correspondingly increased. We can take 100,000 square miles as a reasonable figure for average conditions of 'attack.'*

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[38] See foot-note 11 on page 12.

[39] E.P. Cronkite *et al.*, *Journal of the American Medical Association*, **159,** 430 (1955).

[40] It may be noted in passing that the highest dose to any individual (about 15 persons) in the USA, outside the Nevada Test Site, has been about 7 r; the highest dose for any community (about 200 persons) has been about 4 r.

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* In peace-time tests one would try to so choose the meteoro-

Chart II

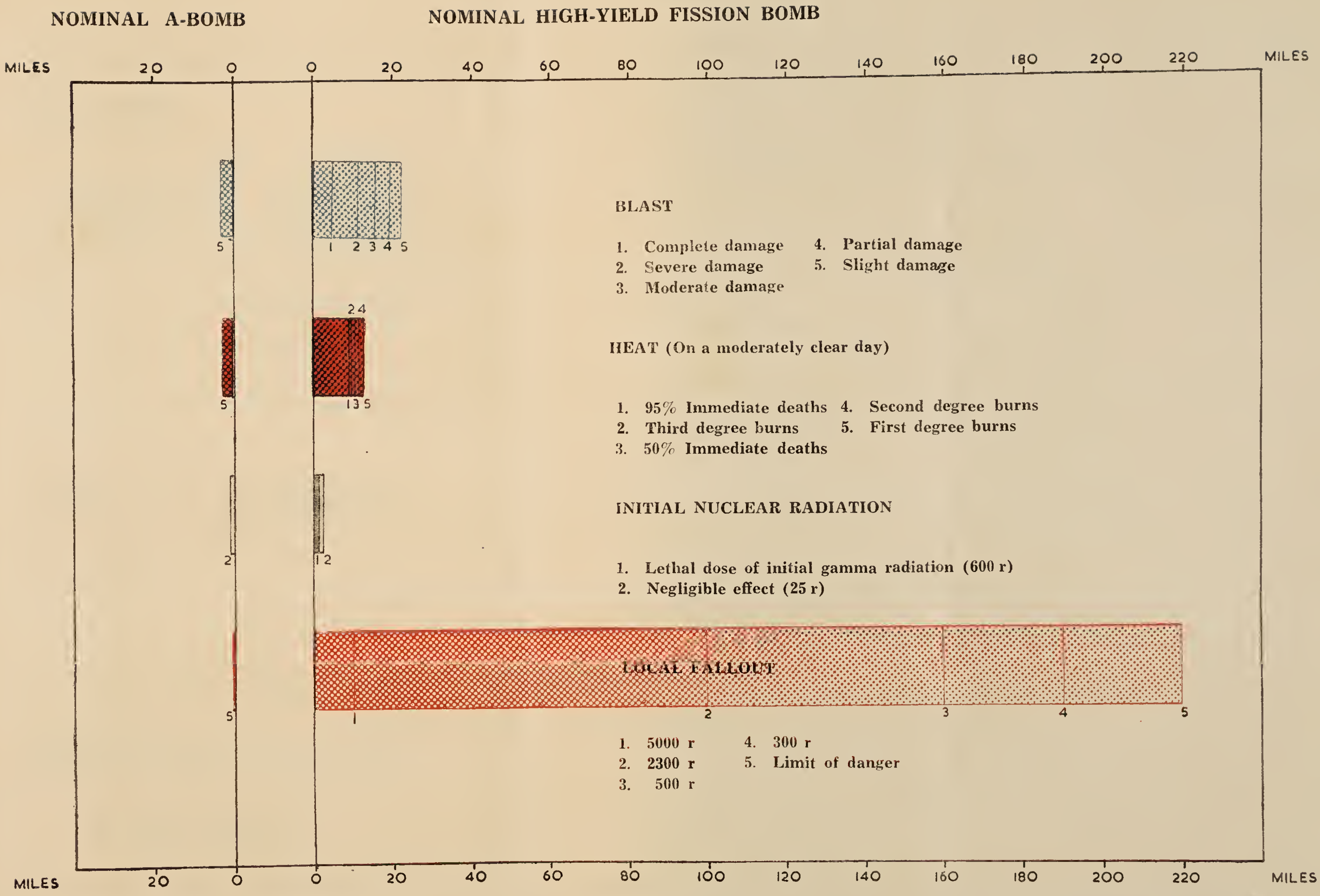


Chart II—Comparison of radii of damage for nominal A-bomb and nominal high-yield fission bomb: In the case of blast, heat and initial nuclear radiation the damage area will be nearly circular; the figures in the chart give the radii of damage zones. In the case of radiological hazard from fallout the pattern would be oval. The figures in the diagram indicate distances along the length of the oval. The width of the oval would be about 40 miles; a head-wind of about 20 m.p.h. has been assumed along the length of the oval. The dose values are for an exposure of 36 hours, and are based on the USAEC Release on the March 1954 Bikini test explosion.

Chart III

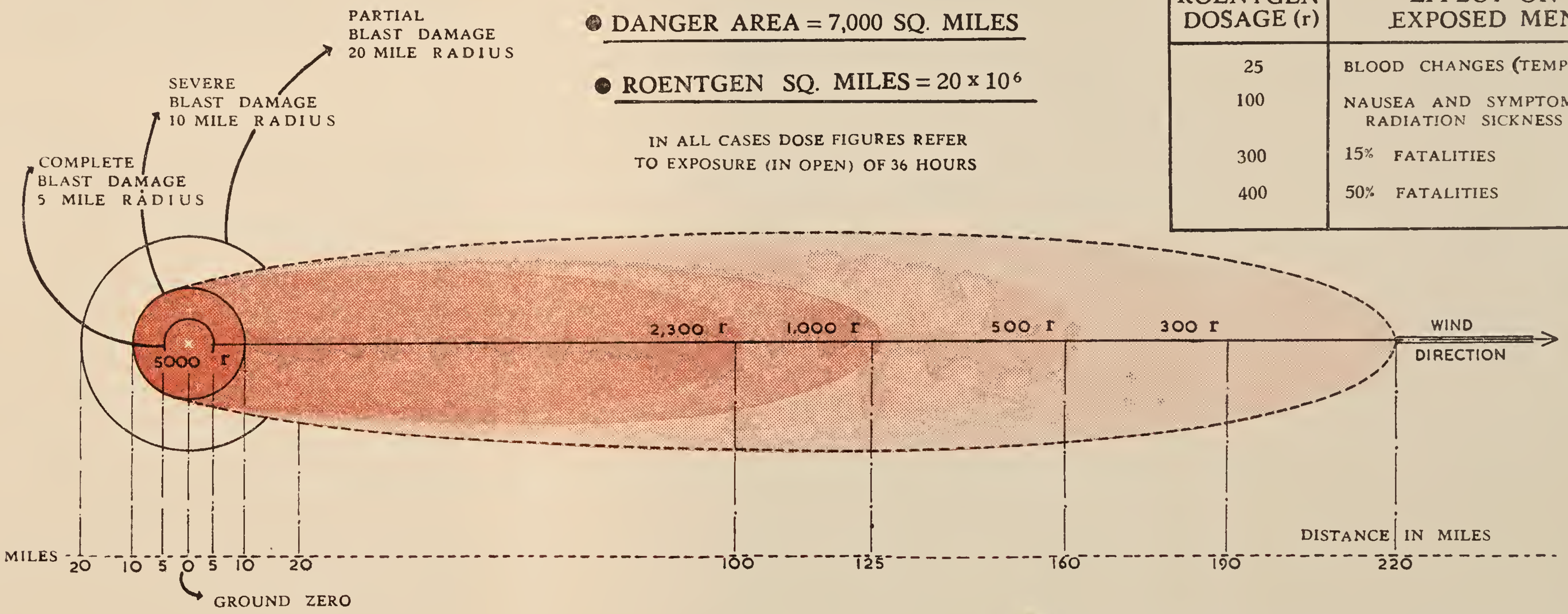
FALLOUT PATTERN FOR US MARCH 1, 1954 EXPLOSION *

(ABOUT 15 MILLION TONS OF TNT EQUIVALENT)

- DANGER AREA = 7,000 SQ. MILES
- ROENTGEN SQ. MILES = 20×10^6

IN ALL CASES DOSE FIGURES REFER TO EXPOSURE (IN OPEN) OF 36 HOURS

ROENTGEN DOSAGE (r)	EFFECT ON EXPOSED MEN
25	BLOOD CHANGES (TEMPORARY)
100	NAUSEA AND SYMPTOMS OF RADIATION SICKNESS
300	15% FATALITIES
400	50% FATALITIES


PARTIAL BLAST DAMAGE 20 MILE RADIUS
SEVERE BLAST DAMAGE 10 MILE RADIUS
COMPLETE BLAST DAMAGE 5 MILE RADIUS
5000 r
2,300 r
1,000 r
500 r
300 r
WIND DIRECTION
DISTANCE IN MILES
MILES
20
10
5
0
5
10
20
100
125
160
190
220
GROUND ZERO

- AT 160 MILES FALLOUT COMMENCED ABOUT 8 HOURS AFTER THE DETONATION AND CONTINUED FOR SEVERAL HOURS
- PATTERN DEPENDS ON WIND STRUCTURE UPTO HEIGHTS OF 80,000 FEET

SIZE OF FIRE BALL : 4 MILES DIAMETER

- FALLOUT PARTICLE SIZE: 1/1,000 - 1/50 INCH

*The chart is a diagrammatic representation based on USAEC Report dated February 15, 1955

All persons in the fallout area would be exposed to a large dose of radiation and must be evacuated in a day or so following detonation, if they are to escape serious consequences. However, evacuation from a vast area of 100,000 square miles of whatever population has survived the blast, heat flash and intense radiation exposure can hardly be considered a practical thing even for highly industrialized countries. Further, where would one find a safe area, in case of war, to provide shelter to this huge mass of evacuated people?

Operation ALERT

In this connection it is instructive to refer to Operation ALERT (June 15, 1955), the first US nation-wide civil defence exercise based on a mock attack using nuclear weapons. It was assumed that 60 cities were struck by 61 bombs varying in size from a nominal A-bomb to a 5 megaton bomb. The warning time (that is, the advance information of the attack) allowed was about three hours. Based on the data collected by the Bomb Damage Assessment Group of the Federal Civil Defence Administration, it was estimated that at the end of the first day of the attack more than 8 million people would have been killed and another 8 million would have died a few weeks later. About a quarter of the deaths would have been caused by radioactive fallout. It was also estimated that the attack would have damaged more than 11 million dwelling units and rendered about 25 million people homeless. In New York alone a 5 megaton bomb (surface burst) would have killed about 3 million people, (38 percent of the population), and injured another 23 percent. Of every 8 New Yorkers about 3 were estimated killed and 2 injured. Civil Defence officials said that the nation was far from being ready to withstand

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logical conditions that the area of fallout is minimum. Under war conditions the opposite would be the case.

a nuclear attack.[41, 42]

Long Term Radiological Hazards: *Global Fallout*

We have so far largely confined ourselves to a consideration of the hazard arising from local fallout. In a nuclear war this would be by far the most serious danger. And again, for local fallout it is the short-term hazard—sickness and death occurring within a few weeks to months of the exposure to fallout radiation—which in all probability would cause a far greater devastation than the late effects (long-term hazard) appearing in the surviving population, years and decades after the exposure.[43]

The situation is different in the case of nuclear test explosions. These are conducted in remote areas and under most carefully worked-out conditions so as to preclude—leaving aside a few rare accidents—any exposure of people to local fallout.[44] However, nothing can be done to avoid exposing almost the entire world population to global fallout resulting from the test explosions. *This global fallout hazard is inherent in the very nature of nuclear tests—particularly multi-megaton tests—and*

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[41] Report on Operation ALERT, 1955 ; also *New York Times*, June 18, 1955.

[42] When referring to a full-scale nuclear assault Lt. Gen. James Gavin (Chief of the US Army Research and Development) in his testimony to the US Senate Sub-Committee investigating comparative air power, is reported to have said: "Current planning estimates run on the order of several hundred million deaths that would be either way depending on which way the wind blew. If the wind blew south-east they would be mostly in the USSR although they would extend into the Japanese and perhaps down into Philippine area. If the wind blew the other way, they would extend well back into Western Europe." (*Hindustan Times*, June 30, 1956).

[43] The long-term hazard discussed in the sequel for global fallout also applies to local fallout (see also Chapter VI).

[44] Not unoften, test explosions have to be postponed if the meteorological conditions (at the time scheduled for the test) become such as to affect adversely the extent of local fallout.

it cannot be eliminated.† Further, as the dose rates involved are extremely low, it is essentially a long-term hazard; its short-term effects can be taken as negligible.

The long-term radiological hazard from global fallout can be divided under two heads: (*i*) external hazard, and (*ii*) internal hazard.

The external hazard is due to the exposure of the population to gamma radiation emitted by the fallout. The dose of gamma radiation received from the global fallout of test explosions is so small that its somatic effect can be almost totally ignored. However, the genetic effect can be appreciable, and even serious. We shall take this up in the next chapter, but it will be appropriate to describe in this chapter the level of gamma dose to which the world population has already been exposed from the tests which have so far been conducted.

Internal Hazard

The internal hazard is due to the absorption into the body of radioactive substances contained in the global fallout. As we shall see presently, the only element which can lead to serious danger is radiostrontium, and further its hazard is somatic and not genetic. It enters the body with the calcium in the food and gets deposited in the bones. Radiostrontium[45] consists of the two radioactive isotopes of strontium with mass numbers 89 and 90, written respectively as strontium 89 and strontium 90. Radiostrontium emits beta rays but no gamma rays.[46]

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† This means—and this is a very important point—that high-yield test explosions cannot be conducted in secret: They will always be out.

[45] The abundance of natural strontium in soil is about 1 part in 10,000. The composition of natural strontium is as follows (the figures in brackets give the relative percentage): Strontium 88 (82.56), strontium 87 (7.02), strontium 86 (9.86), strontium 84 (0.56). Strontium 89 and 90 are unstable and as their half-lives are short they are not present in natural strontium. The half-life of strontium 89 is 53 days and of strontium 90 is 28 years. In fission products strontium 89 and strontium 90 are produced in about the same abundance, but because of the relatively short life of strontium 89, it is strontium 90 which is much the more important.

Radioactive substances can enter the body through

(*i*) inhalation—entry through the process of inspiration (breathing),

(*ii*) ingestion—entry through contaminated foodstuffs and drinks,

(*iii*) injection—entry through wounds, abrasions or direct absorption through the skin.

Under conditions commonly met with in practice, it is entry through ingestion which deserves the most serious consideration. It should be possible with suitable precautions to avoid to a large measure injection of radioactive substances into the body. In the case of inhalation it is known from experiments on animals that particles less than 0·5 micron behave much like gas molecules and move in and out of lungs with the process of inspiration and expiration. Particles bigger than 5 microns are practically all filtered out in the nasal passage. It is only particles within a relatively narrow range of size that are carried to and retained in the lungs, and hence the risk of absorbing any appreciable amounts of radioactive products through inhalation is, generally speaking, small.

Maximum Permissible Body-Burden

In assessing the internal hazard from a radioactive substance the most important thing to know is the

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If we assume that strontium 89 and strontium 90 are present at the start in equal amounts, then at the end of one year the ratio of strontium 90 to strontium 89 would be 115, and at the end of 2 years it would be 1.3×10^4. For longer preriods strontium 89 can be taken as almost non-existent.

[46] As the range of beta rays is very small, the rays emitted by the radiostrontium present in the bones cannot reach the reproductive organs. It is for this reason that any radiostrontium present in the body has no genetic effect.

maximum permissible total-body-burden. We shall denote it by q. It is the quantity of radioactive substance which can be retained in the body for prolonged periods without causing any untoward effects or appreciable bodily injury to a person at any time during his lifetime. In defining q it is usual to take a safety factor of about 10, that is, in a statistical sense, a dose of $10q$ would produce no noticeable effects. For a dose of $20\text{-}30q$ the chances of injury would become appreciable and when the dose is, say, $30\text{-}40q$ the probability of injury would be high. As the radiobiological effect depends on the activity of the radioactive substance, it is useful as well as convenient to express the value of the maximum permissible total-body-burden in curies (or microcuries) rather than by its weight in grams. The International Commission on Radiological Protection (1954) has recommended values for q for a large number of radioactive nuclides. The values vary widely from one substance to another. This considerable variation in the values of q is largely due to the fact that whereas some elements, on entering into the body, are more or less evenly distributed, there are other elements which are localized in some critical organ or organs[47].

The ICRP has also recommended values for the *Maximum Permissible Concentrations* (MPC) for radioactive nuclides in air or water. The MPC value is based on the following assumption: Consider a person exclusively using, for prolonged periods (even extending over a lifetime), air or water contaminated with a given radioactive nuclide, its concentration being equal to the MPC value. Such a person will accumulate a quantity of the given nuclide in the relevant critical body-organ so that it will receive an average dose of 0·3 rem per week. MPC values for some of the important radioelements are given in Appendix VII.

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[47] For instance, the value of q for chlorine 36 (beta emitter) which gets uniformly distributed throughout the body is 230 microcuries; for tritium (tritium-water HTO) the value is 10,000 microcuries. On the other hand for radium (alpha emitter) which gets deposited in the bones the value of q is only 0.1 microcurie. (Recommendations of ICRP (1954), *British Journal of Radiology, Supplement No. 6*, 1955).

It is pertinent to observe that, except for radium, a direct experimental and clinical basis for the ICRP recommendations is almost completely lacking. It is possible that in some cases the q values may be in error by a very large factor. This is not surprising considering that the whole subject of radiotoxicity has been under serious study for only the last one or two decades. Moreover, there is the additional difficulty that it takes a very long time—decades in some cases—for the injury to develop and manifest itself clinically. Even as regards radium, the position is very unsatisfactory—the available quantitative data are very meagre indeed.

At one time in Europe and America radium was widely used, orally and parenterally, under a mistaken belief about its therapeutic value. Also in the early decades of this century workers in the luminous paint industry very often absorbed dangerous amounts of the element in their bodies. It was not until 1932 that the use of radium was removed from its list of new and non-official remedies by the American Medical Association. It is estimated that even now in the USA alone there are thousands of individuals carrying deposits of radium salts (and also thorium salts) in their bodies. However, it is from the case studies of some of these unfortunate people that the present value of q for radium has been arrived at. As H.E. Silberstein *et al.*[48] have observed: "The most important information gathered from all this material may best be summarized by reiterating the basis for setting the currently accepted tolerance level for radium. Seven human cases are known to have carried more than 0·02 and less than 0·5μg (microgram) of radium in their systems for 7 to 25 years without showing any clinical signs of poisoning, yet as little as 1·2μg has been found in a fatal case. The National Bureau of Standards in 1941 therefore set 0·1μg fixed in the body as the maximum safe level of radium content. This figure means a maximum over-all intake of 1μg as the safest limit, and certainly not more than 5μg, inasmuch as permanent fixations of 0·1 to 10 percent of ingested radium have been reported, with an average at about 2 percent. The tolerance level of 0·1μg is diagnosed by the appearance of 1 micromicrocurie of radon per liter of expired air."[49] (1 microgram of radium has an activity of 1 microcurie).

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[48] *Biological Studies with Polonium, Radium and Plutonium*, edited by Robert M. Fink, NNES IV-3, p. 232, (McGraw-Hill, 1950).

An element such as radium is called a bone-seeker as on entering the circulatory system a large portion of it is deposited in the bones. Examples of bone-seekers are: Alpha emitters—radium, uranium, plutonium; beta emitters—strontium, yttrium; beta-gamma emitter—cerium.

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[49] 0.1 microcurie of radium—this corresponds to a mass of ten-millionth gram of radium—emits every minute 8×10^{-15} cc of radon gas (half-life=3.8 days). The activity of the above quantity of gas is 12.6 micromicrocuries. Radon is chemically similar to the rare gases, e.g., argon. It is known that approximately 70 percent of radon liberated from the radium in the body passes out with the expired breath. Taking the volume of expired air per minute to be about 7 liters, it follows that the activity contained in 1 liter of breath is about 1 micromicrocurie. The amount of radium contained in the human body is estimated by measuring the radon exhaled in the breath. Quantities of radium as low as 10^{-10} curie contained in the body can be determined in this way.

It may be mentioned that radium normally present in the body is mostly derived from that contained in drinking water. The concentration of radium in water varies widely, say 10^{-14} — 10^{-11} curie per liter, the figure for the radium content of the human body being 10^{-11} — 10^{-10} curie. The maximum permissible concentration for radium in water recommended by the ICRP is 4×10^{-11} curie per liter of water. The concentration of radium in the soil is of the order of 10^{-13} — 10^{-12} curie per gram. (It may be of interest to note here that the concentration of radon in air usually varies from 10^{-14} — 10^{-12} curie per liter. The ICRP value for the maximum permissible concentration of radon is 10^{-10} curie per liter of air).

If radium is present in the bones for a prolonged period it produces general weakness, bone changes in jaw, malignant tumours and bone cancer (osteogenic sarcoma). Animal experiments have shown that radiostrontium has very similar effects.* It may also induce leukemia. (There are no human data on the toxicity of radiostrontium).

As Finkel[50] has observed: "The relative effectiveness of the radioelements as carcinogenic agents depends upon a variety of physical and biological factors, which are at present only poorly understood. Except for the recognized greater efficiency of alpha particles in inducing malignant bone tumors, the relative importance of the various properties of nuclear radiations remains to be assessed."

It is interesting to recall that in depressing the bone marrow function, experiments on rats have shown that plutonium is 20 times more effective than radium. This difference, it appears, is due to the fact that plutonium is deposited in the surface layers of the bones rather than in the substance and as such its effect is more severe on bone marrow and periosteum.

The elements radium and strontium are chemically akin to calcium. On this account their metabolism in the body follows the same path as calcium. There is some evidence to show that the fraction of the total amount entering the body which is absorbed and retained is somewhat higher in childhood than in later life; also there is a much greater tendency to absorb strontium when the diet is deficient in calium.

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* A single injection of radiostrontium of about 5 microcuries per gram of tissue is almost certain to cause bone tumour in mice a few months after the injection. [It is interesting to note that similar results are produced by radiomimetic chemicals (see Chapter VI)].

[50] M.P. Finkel, "Internal Emitters and Tumor Induction", *Geneva Conference on Atomic Energy*, 1955, Vol. 11,

The *q* values recommended by the ICRP for bone-seeking alpha-emitting nuclides are based on a direct comparison with radium. In the case of other nuclides which include beta and gamma emitters, the *q* values have been calculated on the assumption that the average dose given to the critical organs in which the nuclides get concentrated would be 0·3 rem per week. (We have to use *rem* and not *roentgen*, as account has to be taken of the different biological efficiencies of alpha, beta and gamma rays: See page 78 and Appendix VI). The maximum permissible total-body-burden (*q*) recommended for strontium 90 is 1 microcurie.*

It is important to note that the above *q* values apply only to peacetime occupational exposure, which in practice, would mean mostly adult-exposures. This is, of course, in addition to the natural background radiation to which everyone is subjected. The ICRP has recommended that a reduction factor of 10 should be introduced for prolonged exposure of a large population. This means that in considering the effects of global fallout we must adopt for strontium 90 a value of 0·1 microcurie and not 1 microcurie.[51]

It is apparent from what has been said above that the observational basis for the present *q* values is very scanty.[52] Further, it is most likely that the values will be substantially lower when we are concerned, as with global fallout, with exposures to radioelements for persons of all ages beginning from conception and birth, instead of only adult life which has been mostly the case so far.[53]

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* This is readily derived on the basis of 0.3 rem per week. See Appendix VI.

[51] In this connection the following quotation from E.R. Carling is of interest: "For the moment, it is stated that for large population the figures for permissible doses should be lowered by a factor of ten; that figure may well be altered. For a level in the water of the Thames, which is drunk by one-fifth of the population of the country, a factor of 100 was introduced. The ultimate figure selected will, very likely be decided, not for universal use, but subject to modification for localities depending upon demographic and other conditions. There is at present no firm answer to the question

Young people with bones still growing are much more susceptible than elderly people to damage from bone-seeking radioactive elements such as radium and radiostrontium.

Internal Hazard from Strontium 90

The fission products contain a wide variety of elements. However, it is fortunate that under the conditions of global fallout most of them can cause little harm. If a fission nuclide is to constitute a serious (internal) hazard, it has to satisfy certain rather stringent conditions,[54] namely,

(*i*) it must be produced in appreciable abundance,

'at which value (if any) the *dose-rate* assumes importance?' " (*Geneva Conference on Atomic Energy*, 1955; Paper 8/P/450).

[52] As an instance of the existing uncertainity in *q* values we may note the following: "In the pitchblende mines of Czechoslovakia, where radon concentrations were approximately 10^{-9} curie/liter, the miners had an incidence of lung cancer about thirty times normal. Based on the results of studies in those mines, in this country (USA) we have been using 10^{-10} curie/liter of radon in environmental air. The Europeans use 10^{-11} curie/liter." (*USAEC Health Physics Insurance Seminar*, TID-338, (1951).

[53] Hasterlik in a recent study of about 40 patients, who during 1930-32 were given total dosages of radium ranging from 70-450 microcuries, found that in most cases, at body-burdens of 0.4 microcurie and greater, bony lesions were present. In one case even a body-burden of as low as 0.15 microcurie had produced recognizable injury. In this case the patient received a dose at the early age of about 8 years. (R.J. Hasterlik, *Geneva Conference on Atomic Energy*, 1955. Vol. 11).

[54] For instance, reference to Table VI (p. 48) shows that

(*ii*) its half-life must be sufficiently long — a few decades — so that its effect when retained in the body can be persistent,

(*iii*) it should have a high probability of getting an entry into the body, and

(*iv*) its metabolism in the body should be such that it is readily absorbed, accumulated and retained in some vital organ of the body (e.g., the bones).

There are not many fission nuclides which meet these requirements. In fact there is only one—strontium 90—which really does so.[55] It has a half-life of 28 years. It is produced in about 5 percent of all fission acts. It is a bone-seeker. On entering the body it gets deposited in the bones and stays there for prolonged periods, probably the whole lifetime. Again, because of its chemical similarity to calcium it follows the same metabolic path and gets into the body with the calcium in contaminated (with fission products) vegetables and animal food.

A nominal high-yield fission explosion produces about 19 kilograms of strontium 90, the total activity being

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cesium 137 satisfies all the conditions except (*iv*). Unlike radiostrontium it is readily eliminated from the body. Further, the maximum permissible body-burden for (cesium 137+barium 137) is 98 microcuries as against 1 microcurie for strontium 90. This is largely due to the fact that, whereas strontium concentrates in the bones, cesium goes into the muscles.

[55] The discussion about strontium 90 given here is largely based on W.F. Libby, *Science*, **123,** 657 (1956). Libby has taken the maximum permissible body-burden for strontium 90 to be 1 microcurie —the value recommended by the US Committee on Radiation Protection for AEC Workers, that is, for occupational exposure. We have explicitly adopted one-tenth of the above value for non-occupational exposure.

2.8 million curies* (see Tables VI and XII). Assuming for the moment that all this strontium 90 goes into global fallout and is uniformly deposited (largely brought down by rain) over the earth's surface, the activity per square mile would be 14 millicuries per square mile or 0.5 x 10^{-3} microcurie per square foot. The radiostrontium is absorbed and retained in the top 2—3 inches of the soil. (As radiostrontium is all held in the soil, river water is practically free from it).

We have now to consider how this radiostrontium gets into plants and animals, and ultimately into human bodies. Water-soluble fallout will behave quite differently from water-insoluble fallout: The latter will react very little with soil and plants.[56] Little is known as yet about the actual mechanism of absorption and uptake of metal ions by plants, but as strontium is chemically similar to calcium, it is reasonable to assume that during metabolic processes in plants these elements will, as it were, 'hang together' and not get separated from one another to any appreciable extent.[57] This means that the ratio of strontium to calcium in plants would be nearly the same as that in the soil in which the plants are grown. We shall see a little later that this is not quite so : Plants (and also animals) tend to keep out strontium to some extent. However, for the time being we shall ignore this complication. The amount of calcium in soils — we are not concerned with the total calcium content but the amount which is relevant to uptake by common crops and vegetables, i.e., present in a readily soluble form in the top 2 - 3 inches of the soil—varies considerably with the nature of the soil. The actual value may lie between 2 and 40 grams per square foot. In general soils derived from limestone and igneous rocks contain relatively large amounts of calcium. If we adopt a value of 20 grams per square foot (5.6×10^5 kilograms per square mile) for the available calcium, then 14 millicuries per square mile of radiostrontium gives an activity of 2.5×10^{-2} *microcurie per kilogram of calcium.*

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* The world's present annual output of energy (for heat and power applications) is estimated at 10^{10} megawatt hours. If this were all obtained from uranium fission it would mean a fission of 0.4×10^6 kilograms every year. This would result in the production of 7,600 kilograms of strontuim 90, having an activity of 1,120 million curies.

[56] The solubility property of fallout will be largely determined by the nature of the ground over which the burst takes place, e.g., a burst over a coral atoll (March 1954 explosion) is likely to produce a soluble fallout.

[57] Plants contain a trace of natural strontium (which is non-radioactive), the amount depending on the ratio of strontium to calcium in the soil in which the plants grow. The ratio is roughly one to thousand. The strontium content of animals is governed by the strontium content of plants which they eat. Calcuim is one of the most important constituents of plants and animals; the calcium content of the human body is about 1.5 percent of its

An adult human body contains (in its skeleton) about 1 kilogram of calcium. If we assume that all this calcium is obtained from animal and vegetable food-sources derived from soil deposited with 14 millicuries per square mile of strontium 90, the total-body-burden due to strontium 90 will be 0.025 microcurie. The maximum burden of strontium 90 that an average person can carry for lifetime without any risk of its causing any untoward effects (e.g., malignant tumours) is, as we have seen earlier, 1 microcurie for occupational exposure and 0.1 microcurie for exposure of a whole population. It is this latter value of 0.1 microcurie which is relevant to global fallout. It is too close to the figure of 0.025 microcurie which, according to our foregoing calculation, is the burden everyone is expected to carry as a result of global fallout from one single nominal high-yield test explosion.

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total weight (see Chart IV). A crude but useful picture (for our present purpose) of the uptake of strontium by plants and animals is to regard it as an 'impurity' present in calcium.

If we define a factor of safety S as the ratio of the maximum permissible body-burden (q) to the actual body-burden (Q), the value of S for the case we are considering is 4. This is a somewhat disturbing situation. It demands closer examination. As it stands, it implies that 4 nominal high-yield fission explosions would make S equal to unity and bring us right on to the 'warning line.' (The larger S is compared to unity, the greater is the margin of safety. When S becomes about 0.1 and less, the possibility of the manifestation of harmful effects cannot be ignored. For S equal to 0.01 fatal consequences become almost a certainty).

Let a millicuries per square mile be the activity of strontium 90 in the soil and let b kilograms per square mile be the amount of available calcium of the soil; then the activity due to strontium 90 per kilogram of calcium in the soil is given by a/b (millicuries per kilogram of calcium). The question now is: What would be the activity per kilogram of calcium contained in crops and vegetables grown on this soil? Some recent work sponsored by the USAEC seems to indicate that, in general, plants discriminate to some extent against the uptake of strontium as compared to calcium. The ratio of strontium to calcium is less (possibly one-half) in plants than what it is in the soil. Sometimes, however, the radiostrontium content of crops and leafy vegetables can be appreciably higher than that of the soil in which they grow. This is due to direct absorption by the plant of radiostrontium in the (water-soluble) fallout deposited on its foliage, the process being similar to assimilation of leaf-fertilisers.

It appears that animals also discriminate against the absorption of strontium in relation to calcium.* Thus the radiostrontium content of milk and cheese has been found to be about 1/5 to 1/10 of that in the grass on which the animals were fed.* The overall effect of this is to cut down substantially the amount of radiostrontium carried into the human body per unit mass of calcium. If k denotes this reduction factor, that is, the ratio of radiostrontium in the human body to radiostrontium in the soil (both referred to unit mass of contained calcium), then the value of k lies between about 0.1 and 0.5 depending on whether the body-calcium is mostly derived from animal food or vegetables. Inserting this factor k, we have for the radiostrontium burden of a *standard man* (total calcium content 1 kilogram) the value ka/b millicuries, and taking the maximum permissible body-burden for non-occupational exposure to be 0.1 microcurie we get for the safety factor S the expression[58]

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* This is an extremely important point and needs to be firmly established.

$$S=(b/ak)\times 10^{-4}$$

The value of S will depend on the values we adopt for the quantities a, b and k. Let us first take the quantity a, the radiostrontium deposited per square mile of soil surface.

The rate of global fallout since the 1954 high-yield test explosions (USA) has been measured at several widely scattered places, and according to Libby the average value is 1.5 *millicuries of radiostrontium per square mile per year.* This figure taken with other relevant data indicates, as Libby has observed, that in a high-yield fission explosion about half of the fission products go into global fallout, and further the fallout extends over a period of roughly 10 years. Notice that the fall in the activity of strontium 90 during this 10-year period is negligible, its half-life being 28 years. The figure of 1.5 millicuries per square mile per year corresponds to two nominal high-yield explosions. The total activity of strontium 90 from two such explosions would be 2 × 2.8 million curies. Assuming that half of the fission products are projected into the stratosphere and then gradually return to earth over a period of 10 years at a nearly uniform rate, the annual rate of deposition of radiostrontium would be about 1.5 millicuries per square mile per year. It is likely that following the USSR (November 1955) and USA (May 1956) high-yield explosions (air bursts) the present rate of world-wide fallout is about 3–5 millicuries of radiostrontium per square mile per year.

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* These values refer to cow products. It is necessary to determine the same for other 'milk suppliers' e.g., buffalo.

[58] It is assumed that the intake of radiostrontium-contaminated calcium has been for a period long enough for the calcium in the body to be exchanged with the contaminated calcium. The normal daily intake in food of calcium for an adult person is about 0.8 gram. As the body contains about 1,000 grams of calcium, it follows that it requires a few years for a turn over (exchange with outside) of calcium in the body to take place.

It is not quite easy to estimate the period for which, on an average, radiostrontium stays in the soil before it gets buried relatively deep or is otherwise dispersed so as to become ineffective for uptake by plants. If this period extends over a number of years, it would lead to a corresponding accumulation of radiostrontium in the soil. We shall adopt, as a reasonable (conservative) estimate, an average value of 5 millicuries of radiostrontium per square mile as a likely figure applicable to the next decade or so, provided no further high-yield tests are conducted — the actual value may be 2 to 3 times higher. For each nominal high-yield fission explosion, the value of a would be increased (again on a conservative basis) by about 2 millicuries per square mile. In the case of the USA, because of local and semi-global fallout from Navada tests, the value of a may be taken as roughly 3 times the average value for the world as a whole. (The value for Australia is also likely to be higher because of the fallout from the Monte-Bello and Woomera tests).

In this connection the following observations of Libby[59] are extremely important. "We find, therefore, that the radiostrontium content of human bodies is the lowest of all animals measured and is lower than the average soil and average foliage by tenfold. The strontium 90 to calcium ratio in young people—whose bones are still forming—corresponds to about 1/1000 of the maximum permissible concentration recommended for adults—1 microcurie per standard man containing 1,000 grams of calcium. The average soil in the United States contains about 10 times more, whereas abroad the radiostrontium content in other areas of the world not subject to the local test fallout is about one-third of that for the United States." Assuming 20 grams of available calcium per square foot of soil (*i.e.*, 1 ton per acre), the above value of 10^{-2} microcurie of radiostrontium per kilogram of calcium gives for USA 6 millicuries of radiostrontium per square mile. For areas not subject to local fallout, the value is one-third of the above, that is, 2 millicuries per square mile: This value refers to the fallout from the March 1954 explosions only. The value of 5 millicuries per square mile adopted by us for the fallout from all high-yield explosions up to mid-1956 is thus reasonable.

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[59] W.F. Libby, *Science,* **123,** 657 (1956).

We have now to consider the value to be assigned to b, the amount of available calcium per square mile of soil. The value of b is likely to lie between 0.5×10^5 and 10^6 kilograms per square mile (that is, 2-40 grams per square foot). We shall calculate S for these two extreme values. The lower value of b corresponds to calcium-deficient soils.

We now come to k. The value of k depends on the relative contribution to the average diet of calcium from animal-source (milk and milk products) and vegetable-source. We shall calculate S for $k = 0.1$ and $k = 1.0$ corresponding to animal-source and vegetable-source of calcium respectively. In countries with a high level of nutrition more than half of the daily intake (0.8 gram) of calcium is from milk and cheese. (A pound of milk contains 0.5 gram of calcium: The calcium content of hard cheese is five times higher. A pound of wholemeal wheat flour has 0.2 gram of calcium, whereas 70 percent extraction-flour has 0.08 gram).

The values of S calculated on the above assumptions are given in Table XVII.

TABLE XVII

S values for different values of b and k

($S=\frac{b}{ak}\times 10^{-4}$ and $a=5$ millicuries per sq mile)

k / b	0.1	1.0
0.5×10^5	10	1
10×10^5	200	20

It will be seen that the lowest value for S is 1 and the highest value is 200. It should be again stated that these values are based on the maximum permissible body-burden being equal to 0.1 microcurie: For reasons which have been indicated to some extent in earlier paragraphs this value is uncertain by a considerable factor. (For instance, if this were one-tenth of the presently accepted ICRP value — a possibility which cannot be altogether ignored, particularly for exposures taking place in infancy and childhood when bones are actively forming— it would mean that we have already crossed the danger point). If further tests, even on the present scale, are continued, then the possibility cannot be dismissed that, at the end of a decade or so, the radiostrontium body-burden may exceed the permissible burden by an appreciable factor causing a noticeable rise in skeletal injuries and other untoward effects. These are first likely to appear in populations having a comparatively low standard of nutrition.

The estimate of radiostrontium hazard is beset with many uncertainties and difficulties. All the same, it is apparent that it constitutes a danger to which the most careful attention must be given. It is a subject which deserves and demands a serious and sustained study on a world-wide basis.

Radioiodine Hazard

We have discussed at some length the global fallout of strontium 90. From the point of view of radiological hazard this is by far the most important of fission nuclides. The only other fission nuclide worth considering is iodine 131. (We shall also say a few words about radiocarbon; but it is not a fission nuclide). Iodine has a number of radioactive isotopes with different half-lives. All of them are produced during the process of fission, but it is only iodine 131 which has a sufficiently long half-life — even this is only 8 days — to be of biological significance. Iodine 131—we shall also speak of it as radioiodine[60] — emits beta and gamma rays (see Table VI, p. 48). Radioiodine can enter the body through inhalation or ingestion (of contaminated dust). On entry into the body it accumulates in the thyroid gland for which it has a remarkably strong preference. The thyroid is relatively insensitive to radiation and it can take in large doses without any apparent harm. For instance, in the case of sheep, about 16,000 r have to be given to produce a noticeable damage. The treatment of hyperthyroidism in man requires a dose as large as 5-10 thousand r from iodine 131. The radioactivity due to iodine 131 in fallout has been detected in thyroids of cattle and sheep, and also human thyroids (in autopsies). When the activity in cattle thyroid is continuously studied over a long period, there occur, corresponding to the test explosions, peaks in the activity *versus* time curve. An interesting account of some recent measurements has been given by L. Van Middlesworth[61] The *maximum* dose of iodine 131 received by thyroids of cattle and sheep in Europe as a result of global and semi-global fallout is of the order of 10^{-3} microcurie per gram of thyroid. For the US the figure is about ten times higher. In the case of human thyroid, as Middlesworth has observed " the maximum iodine 131 per gram of human thyroid was less than 0·5 percent of the maximum for cattle from the same general area. This difference may be related to the fact that the human thyroid[62] is more than 10 times larger than that of cattle (compared on body weight basis), but the total volume of air inhaled per day is less in the human beings. In addition, human beings do not ingest large amounts of dust in their diet."

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[60] Strictly speaking radioiodine is a mixture of radioactive isotopes of iodine. However, as these isotopes, except iodine 131 have (in comparison to iodine 131) short half-lives, their concentration, as compared to iodine 131, becomes altogether negligible in less than a week from the time of production (e.g., fission explosion) of radioiodine.

The maximum doses mentioned above are too small to produce any detectable effects.

Uranium/Plutonium Hazard

Apart from fission products, there will also be present in the fallout uranium and/or plutonium as considerable quantities of these elements would be left unfissioned at the end of the explosion. However, their radiological hazard is negligible. Take first plutonium. It is a bone-seeker and the maximum permissible body-burden is 0·04 microcurie which corresponds to a mass of about 0·5 microgram. As less than 1 percent of the ingested quantity is fixed in the body, an ingestion of about 0·1 milligram is required to provide the maximum permissible body-burden. If a man were to receive this much amount of plutonium with his food in 30 years, then the average concentration of plutonium in the ash of food eaten has to be (assuming that the quantity of food eaten in 30 years is 30×500 kilograms of which 1 percent is ash) about 10^{-9} gram per gram of ash. Taking the concentration of plutonium in the food-ash to be the same as in the soil, and further assuming that plutonium is confined to the top 1 cm of the soil, the amount required to be deposited in global fallout comes out to be of the order of 3,000 tons. (The above argument closely follows AW (1950), p. 436). Thus plutonium hazard from nuclear test explosions is practically negligible. The same holds with much greater force in the case of uranium 235. In fact, uranium is more a chemical poison — about as dangerous as lead — than a radiological hazard.

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[61] L. Van Middlesworth, *Science*, **123**, 982 (1956).

[62] The average weight of a human thyroid gland is about 20 grams. It requires about 0.03 microcurie (of iodine 131) per gram of thyroid to produce a dose rate of 0.3 r per week (the maximum permissible dose rate).

Radiocarbon Hazard

We shall now say a few words about carbon 14 (radiocarbon). This is not a fission nuclide, but is produced by the capture of neutrons by nitrogen in the atmosphere:

$$\begin{aligned} N^{14}+n_0 &\longrightarrow C^{14}+H^{1}+0.61 \text{ mev} \\ C^{14} &\longrightarrow N^{14}+\beta^{-}+0.16 \text{ mev} \end{aligned}$$

It emits beta rays of (maximum) energy 0·16 mev, the average energy being 0·05 mev. It has a half-life of 5,600 years. It is reasonable to assume that almost all the neutrons which escape from the bomb cloud are ultimately captured by nitrogen and form radiocarbon. A nominal high-yield fission explosion liberates about 10 kilograms of neutrons, and if we suppose that 10 percent can get out of the bomb cloud, then the amount of radiocarbon produced would be 14 kilograms. (An all-fusion explosion of the same energy would liberate roughly 10 times more neutrons and produce ten times more radiocarbon).

Radiocarbon is being formed continuously in the atmosphere by capture of neutrons which are produced by cosmic rays in their interaction with matter in the atmosphere. There cannot, however, be a continuous accumulation of radiocarbon. As it decays with a half-life of 5,600 years, an *equilibrium value* is reached in less than a hundred thousand years such that the amount produced in a given time equals the amount decaying in the same time.[63] As a hundred thousand years is a very short period as geological time-scales go, the observed value for radiocarbon must be the equilibrium value. It is estimated that the earth has on its surface (in the atmosphere, biosphere[64] and oceans) about 80,000 kilograms of carbon 14 ; this corresponds to an activity of 7 micromicrocurie per gram of natural carbon.[65]

The atmosphere—that is, the carbon dioxide in it—contains about 1,200 kilograms of radiocarbon—it is 1.5 percent of the total radiocarbon on the earth's surface.

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[63] Let p be the rate per second of formation of radiocarbon due to the action of cosmic rays and N the equilibrium value of radiocarbon; we have

$$\lambda N = p$$

where λ is the decay constant (half-life$=0.7/\lambda$).

It is reasonable to assume on the basis of available evidence that the intensity of cosmic rays has remained nearly constant over geological periods.

[64] The biosphere—that is, the layer of vegetation and living organisms on the earth's surface—is estimated to contain something like 10^{11} tons of carbon; the radiocarbon in it would be about 100 kilograms. This is 0.1 percent of the total radiocarbon on the earth's surface.

[65] Natural carbon contains no radioactive isotope other than carbon 14 which is present to the extent of 1 part in 10^{12}. It is important to observe that the carbon 14 content of natural carbon has the 'equilibrium value' provided it is continually participating in an exchange with the carbon in the atmosphere, for it is only in the atmosphere that radiocarbon is generated. If carbon containing the equilibrium value of radiocarbon is prevented from taking part in this exchange, then its radioactivity would fall with a half-life of 5,600 years. This provides a powerful method of dating wood lying buried under ground (as in caves) for a few thousand years.

As a nominal high-yield fission explosion results in the production of about 14 kilograms of radiocarbon, we would require 90 such explosions to double the radiocarbon content of the atmosphere. (It would need about 6,000 explosions to double the total radiocarbon present on the earth's surface). Even this doubling would cause no noticeable radiological effects. The human body contains about 12 kilograms of carbon more or less uniformly distributed. The carbon 14 normally contained in it gives a total body-burden of 0.1 microcurie causing an exposure of 1.5 milliroentgens per year. This, however, is less than one-tenth of the exposure due to radiopotassium (potassium 40) present in the body (see Chart IV). Thus we conclude that any hazard due to radiocarbon generated by nuclear test explosions is practically negligible.[66]

Dose due to Global Fallout

As a prelude to the following chapter we shall now discuss the level of whole-body-exposure to which people are subjected due to global fallout from nuclear explosions. We shall see that the dose so far received is far too small to have any noticeable somatic effects, but the genetic consequences may not be altogether negligible.

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[66] In this connection it is interesting to observe, as has been beautifully shown by recent measurements on the variation with depth of the concentration of tritium water in sea water—tritium (half-life 12.4 years) is produced in the atmosphere by action of cosmic rays and then combines with oxygen to form radioactive water—that whereas there is complete mixing (due mainly to turbulence) in the top 100 meters or so of sea water, the lower layers are in a state of virtual isolation from the 'top layer'. The carbon dioxide in the top layer is in continuous exchange with the carbon dioxide in the atmosphere. The two are also nearly equal in amount. Any radiocarbon produced in the atmosphere would get about equally distributed in a few weeks or months between the atmosphere and the top layer of the sea. This would in effect double our estimate of the number of explosions necessary to double the radiocarbon content of the atmosphere.

We have already said earlier that the internal hazard arising from ingestion of fission products (radiostrontium being the most important) has no genetic component; the radiation cannot reach the reproductive organs. This is no longer true when we deal with exposure to gamma rays from fission products scattered in the environment.

To appreciate the orders of magnitude involved, let us consider a nominal high-yield explosion. As we have seen, in general about 50 percent of the fission products go into global fallout. The fallout is deposited —more or less uniformly over the entire globe — at a gradual rate, beginning a few weeks from explosion and extending over a decade or so. However, to keep the argument simple without sacrificing any essentials, let us suppose that the fallout is deposited in one lot at the end of one month from the date of explosion. This would mean a spread of radioactivity over the earth's surface of about 6 curies per square mile (see Chart I). Because of this radioactivity a person in the open would be subjected to a whole-body-exposure at the rate of 0.6 milliroentgen per day. As radioactivity decays with time, the total dose which would be received over an indefinitely long period — we shall speak of it as *eternity dose* or *infinity dose* — is not infinitely large but will only add to about 100 milliroentgens in all.[67]

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[67] It may be worthwhile to consider a little more in detail the above—rather important—illustrative example.

For a nominal high-yield explosion the gamma ray activity of fission products at t hours from detonation is given by (see Chart 1(a)) the expression $6 \cdot 0 \times 10^{12}/t^{1 \cdot 2}$ curies. Roughly speaking, the expression holds for t values from about 10 seconds to about a year. If we assume the fission products to be uniformly deposited over the earth's surface (200 million square miles), the activity is $3 \times 10^4/t^{1 \cdot 2}$ curies per square mile of the surface. As 10^4 curies per square mile give for a person in the open a dose rate of 0.04 r per hour, we have for the global fallout under consideration a dose rate of nearly $0 \cdot 1/t^{1 \cdot 2}$ r per hour (t is in hours), and hence the total dose received for an exposure

In discussing radiation hazard, the (mathematical) concept of eternity dose is a useful one. It gives the theoretical upper limit to exposure; the actual exposure even extending over a lifetime would be appreciably less

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from time t to T is (in roentgens)

$$0.5\left(\frac{1}{t^{0.2}}-\frac{1}{T^{0.2}}\right).$$

The 'eternity dose' R (that is, for T very large compared to t so that $(t/T)^{0.2}$ is small compared to unity) is given by (t in hours)

$$R=0.5/t^{0.2} \text{ roentgen.}$$

In the following table we give values for R for different values of t. We have also added for comparison values of the dose R_1 received in a period of 30 years beginning from the time t.

t	1 hour	1 day	1 week	1 month	1 year
R	0.50	0.27	0.18	0.13	0.08
R_1	0.46	0.22	0.14	0.09	0.04

It may be stated that "the principal contributors to gamma dosage within the first year are 35d Nb^{95}, 65d Zr^{95}, 42d Ru^{103}, and 30d Ce^{141} with ($\sim$ 1 yr) Ru^{106} and 275d Ce^{144} predominating thereafter (95 percent of the gamma activity at three years will be due to these two nuclides). Ten years after the detonation the gamma activity will be dominated by 33 yr Cs^{137}." (R.E. Lapp, *Bulletin of the Atomic Scientists*, **11**, 339 (1955)).

As the $1/t^{1.2}$ law is not valid for t greater than about a year, it is worthwhile to estimate the eternity dose for exposure beyond 1 year by adding the separate contributions due to cerium 144 and cesium 137. Take the case of cerium 144. A nominal high-yield explosion liberates about 110 million curies of cerium 144 (see Table VI, p. 48). If we suppose that the material is uniformly deposited over the earth's surface, the eternity dose $R(t)$ (in roentgens) will be given by

$$R(t)\sim 0.02\, exp(-\lambda t)$$

where $\lambda\sim 10^{-4}$ (hour)$^{-1}$. For $t=1$ year the eternity dose is about 0.01 r. The contribution due to cesium 137 is similarly found to be 0.03 r. Thus the total eternity dose due to cerium 144 and cesium 137 is 0.04 r. This is about one-half of the value given in the above table.

than this limiting value. However, in most cases it would make no serious error to take the lifetime dose as equal to the eternity dose.

It is apparent from the above example that the eternity dose due to global fallout from a high-yield explosion can only be a small quantity—a small fraction of a roentgen at the most. At this stage we should also mention two important factors which considerably cut down the exposure to which people are subjected. These may be referred to as (*i*) weather, and (*ii*) shelter.

In our example we assumed that all the fallout was deposited on the earth's surface in one lot, and that where it fell it remained (fixed, as it were) for prolonged periods, say decades. Now, the actual precipitation of global fallout from a high-yield explosion is spread out over a period of about 10 years. Because of the continuous scavenging action of rain, winds and weather it is not to be expected that any large accumulation of fallout will take place over any long period. (We are here considering the fallout from one single explosion). It is difficult to estimate as to how far this accumulation does actually occur: It would obviously vary widely from one region to another. Again, people do not stay in the open for all the time: The fraction of the time they do so varies widely with the climate in which they live. Further, the protection against fallout gamma radiation offered by a dwelling is also a widely variable quantity. A village hut with its relatively thin walls and thatched roof offers negligible protection (see page 104). These are all uncertain factors. (Further research and large-scale surveys of relevant factors may considerably reduce this uncertainty). It is likely that the overall effect of the exposure-reducing influences is to cut down the dose by a factor of about 10, giving a figure of roughly 10 milliroentgens for the lifetime dose in the open due to global fallout from one nominal high-yield fission explosion: The total dose from all the test explosions so far conducted would be of the order of 100 milliroentgens. This figure would apply to people living in dwellings too flimsy to afford any radiation protection. An average city house may cut down the dose by a factor of 10.

A much more reliable estimate has been provided by Cockroft[68] in an address to the UK Parliamentary and Scientific Committee. He estimated a total dose of 0.03 r — the dose from all atomic explosions being only one-fifth of the dose from high-yield explosions — for people (in open) in Britain from all nuclear explosions to date[69] (April 1955). " In the United States, where local fallout from Nevada is important, the average dose received from bombs so far exploded will total 0.1 r. The actual dose varies by a factor of 2 in different areas."

If we add to Cockroft's figure the dose resulting from the USA and USSR high-yield test explosions conducted subsequent to his estimate, it is reasonable to adopt a value of 0.1 r as the lifetime dose (for people in the open) due to global fallout from test explosions

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[68] J. Cockroft, *Nature*, **175**, 873 (1955).

[69] The following table, adapted from Harwell Report AERE-HP/R 1701 (June 1955), is reproduced from R.E. Lapp, *Bulletin of the Atomic Scientists*, **11**, 339 (1955). It gives for Britain the dose in the open due to global fallout from high-yield test explosions.

Test Series		Dosage Interval	Dose
Origin	Date		
Eniwetok, USA	Nov. 1, 1952	Total	6.16 mr
Bikini, USA	March 1, 1954 (beginning)	Mar. 13, 1954 to Sept. 16, 1954	0.92 mr
		Sept. 20, 1954 to Jan. 6, 1955 (interpolated)	0.92 mr
		Jan. 6, 1955 to Feb. 15, 1955 (deposited)	0.38 mr
		Exrapolated to future	20.30 mr
		Total	28.68 mr

In connection with dose from global fallout reference should up-to-date. (Although no official figures for the total number of test explosions is available, yet the number up to June 1956 is generally estimated to be about 90 (US—70; USSR—17; UK—3), of which 12 are of the high-yield fission type). We should, however, recognize that because of the many uncertainties involved this estimate may be in error by as much as a factor of 5 or so. The dose for the USA would be appreciably higher, maybe by a factor of 2 to 3, because of the (local and semiglobal) fallout from Nevada tests. Also the dose in temperate latitudes in Northern hemisphere, because of the semi-global fallout, would be somewhat higher than in the tropics and Southern hemisphere.

Natural Dose

When we come to discuss the effects on the individual of the global fallout dose, it is extremely important to compare (*i*) the magnitude of this 'artificial' or man-made exposure and (*ii*) the dose that the individual receives from the naturally (and normally) present radioactivity in his own body and the radioactivity and cosmic rays in the environment. We find that the lifetime dose received from exposure to this *natural background radiation* — for brevity, we shall speak of it as *natural dose* — is very much higher than the lifetime dose from the nuclear test explosions so far carried out.

The natural dose is due to three distinct agencies[70]:

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also be made to the following:

(*i*) M. Eisenbud and J.H. Harley, "Radioactive Dust from Nuclear Detonations", *Science*, **117**, 141 (1953).

(*ii*) M. Eisenbud and J.H. Harley, "Radioactive Fallout in the United States", *Science*, **121**, 677 (1955).

(*iii*) I.H. Blifford, Jr. and H.B. Rosenstock, "Fallout Dosages at Washington, D.C.", *Science*, **123**, 619 (1956).

[70] W.F. Libby, "Dosages from Natural Radioactivity and Cosmic Rays", *Science*, **122**, 57 (1955). (The present treatment closely follows Libby).

(*i*) radioactive substances present within the body,

(*ii*) cosmic rays,

(*iii*) ionizing radiations emitted by radioactive substances present in the surroundings (*e.g.*, rocks, soil, building materials).

Radioactive Substances Within the Body

There are two radioactive nuclides, potassium 40 and carbon 14, which are naturally present in the body, potassium 40 being much the more important of the two. It occurs to the extent of 0.012 percent in natural potassium. It emits beta rays (maximum energy 1.36 mev) and gamma rays (K-electron capture: gamma energy 1.45 mev). (The half-life for gamma-decay is about 10^{10} years and about one-tenth of this for beta-decay). One gram of natural potassium emits about 30 beta rays and 3 gamma rays per second. The amount of potassium in the body is about 2 grams per kilogram weight. (The 'standard man' (Chart IV) contains 140 grams of potassium, and hence has a total radioactivity of about 0.01 microcurie for gamma rays and 0.1 microcurie for beta rays). Following the method described in Appendix VI we can readily calculate the dose which a person receives from his potassium content. It comes out to be 17 milliroentgens per year from beta rays and 2 milliroentgens per year from gamma rays.[71] The carbon 14 in the body — its total activity in the body is about 0.1 microcurie — contributes a dose of another

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[71] The gamma dose is calculated on the assumption that only fifty percent of the gamma rays are absorbed in the body : The remaining fifty percent escape from the body. (A 'standard man' is thus a gamma ray source of strength 0.005 microcurie, radiating to the surroundings about half a million gamma ray photons every hour). It thus follows that in a packed crowd a person receives from the potassium in his neighbours a gamma dose at a rate of 2 mr per year. (W.F. Libby, *loc. cit.*).

1.5 mr per year. The activity of radiocarbon and radiopotassium is about the same, but the dose due to the latter is roughly ten times larger because of its larger beta energy. Thus the total dose received by the body is about 20 milliroentgens per year.

Recently the gamma rays emitted by the human body have been directly measured.[72] Sievert[73] found the gamma radiation per unit body-weight from male subjects (10^{-10} curie per kilogram weight) to be about 20 percent higher than in female subjects: It also decreased with age beyond about 60 years. "This is easy to understand if we consider that most of the potassium in the human body is to be found in muscle tissue and that the fat has a low potassium content. From old people with atrophied muscles and from heavy subjects having much subcutaneous fat absorbing the gamma radiation, the gamma radiation is lower than from young and middle-aged subjects."

The body, in general, also contains a quantity of radium derived from drinking water. This has been variously estimated as between 0.01 microcurie and a value one-hundredth of this. However, Sievert (*loc. cit.*) on the basis of measurements on a few hundred subjects finds that: "It seems correct to assume that if the water ingested during life has a radium content less than 10^{-12} curie per liter, the radium stored in the body cannot, even in old people, give a higher contribution to the potassium 40 radiation than 10 percent."

In view of the uncertainty involved—and in any case as the contribution is only a small fraction of that due to potassium—we shall ignore the dose from exposure to radium within the body.

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[72] F. Reines *et al.*, "Determination of Total Body Radioactivity Using Liquid Scintillation Detectors", *Nature,* **172**, 521 (1953).

[73] R.M. Sievert, "Measurement of Low Level Radioactivity, Particularly the γ-radiation from Living Subjects", *Geneva Conference on Atomic Energy,* 1955; Paper 8/P/792.

Cosmic Rays

The intensity of cosmic rays depends upon the latitude and altitude of the place. This is minimum at the equator and sea level, and increases with increasing latitude and altitude. At sea level the number of ions produced in air by cosmic rays is about 2 ion-pairs per cc per second. The roentgen is defined as 2.1×10^9 ion-pairs per cc of air, and hence the dose from cosmic radiation at sea level is about 30 mr per year. At higher latitudes it would be larger. The values for different latitudes and altitudes are given in Chart IV.

Gamma Rays Emitted from the Earth's Surface

Rocks and soil contain radioactive nuclides, the most important being uranium (with its daughter-products radium and other nuclides), thorium (with its daughter-products) and potassium. As described in Appendix VI the dose due to gamma rays emerging from the earth's surface can be readily calculated. It is largest for granite rock—about 90 mr per year. The ocean has (in comparison to land surfaces) negligible concentrations of radioactive substances, and as such the dose at sea is practically zero.

Summarizing, we find that the total dose which a person receives from the natural background radiation is about 0·1 roentgen per year, that is, roughly 4 r from conception to the age of about 30-40 years. This figure can be taken as a rough world-average.[74] In some regions the dose is likely to be substantially larger, *e.g.*, Tibet (due to increased cosmic ray intensity because of altitude) and some parts of Travancore, India (due to the relatively high radioactivity of monazite sands).

We conclude that the natural dose is much larger than the dose to which the world population has so far been subjected from nuclear explosions.

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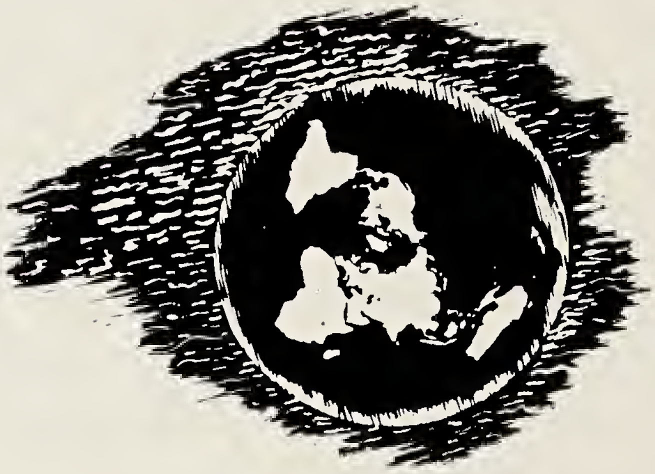
[74] It is of interest to note that Sievert (*loc. cit.*) by direct measurement found the intensity of background gamma radiation in Swedish

Appendix IV deals very briefly with the possible effects of nuclear explosions on weather. The general conclusion is that the explosions so far have produced no noticeable modification of weather.

Appendix V deals with the radioactivity of marine organisms arising from the contamination (by fission products) of sea water.



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houses to lie between 0.05 and 0.5 r per year depending on the type of house, the dose rarely exceeding 0.25 r per year.

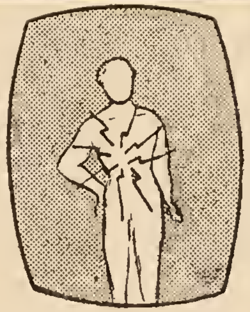
He also observed that in very badly ventilated houses, the radon concentration may become very high, approaching the maximum permissible concentration for occupational exposure (10^{-13} curie per liter of air) recommended by the ICRP: The gamma ray background, however, was only 0.2 r per year. As radon is practically not retained in the body — it goes in and out with breath — it is only the lungs which are exposed to its alpha radiation.

Chart IV

LEVEL OF EXPOSURE OF HUMAN BODY TO BACKGROUND RADIATION

[DOSE UNIT : MILLIROENTGEN PER YEAR]

I
RADIOACTIVE ELEMENTS IN THE BODY

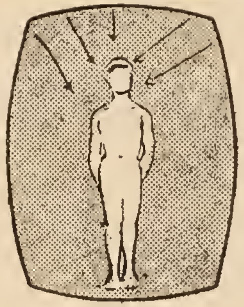


RADIOACTIVE CARBON (15 DISINTEGRATIONS PER MINUTE PER GRAM OF CARBON) 2

RADIOACTIVE POTASSIUM (1980 DISINTEGRATIONS PER MINUTE PER GRAM OF POTASSIUM) 19

RADIUM (3.7×10^{10} DISINTEGRATIONS PER SECOND PER GRAM OF RADIUM) 7 (?)

II
COSMIC RAYS



	EQUATOR	HIGH LATITUDES
SEA LEVEL	33	37
5,000 FT.	40	60
10,000 FT.	80	120
15,000 FT.	160	240
20,000 FT.	300	450

III
RADIOACTIVE RADIATIONS FROM EARTH'S SURFACE

GRANITE ROCK 90
ABUNDANCE IN PARTS PER MILLION

U	Th	K
4	13	3×10^4

(TYPICAL)

SEDIMENTARY ROCK 23
(U, Th AND K ABOUT 1/4 AS ABUNDANT AS IN GRANITE)

OCEAN 0
ABUNDANCE IN PARTS PER MILLION

U	Th	K
2×10^{-3}	10^{-5}	4×10^2

URANIUM (ORE CONTENT 0.1 %U) ROCK:
ROCK SURFACE 2,800
INSIDE MINE (2×2,800) 5,600

PHOSPHATE (FERTILIZER) ROCK: 280 — 700
(U CONTENT ABOUT 0.01-0.025%
ROCK SURFACE

TOTAL
I +II+ III

AT EQUATOR (SEA LEVEL)

21+ 33+90= 144

21+ 33+23= 77

21+ 33+ 0= 54

AVERAGE CHEMICAL COMPOSITION OF THE ADULT HUMAN BODY

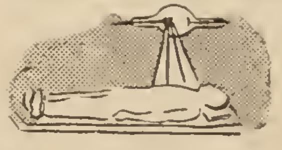
ELEMENT	PERCENT BY WEIGHT	APPROXIMATE AMOUNT IN A 70 Kg MAN gm	ELEMENT	PERCENT BY WEIGHT	APPROXIMATE AMOUNT IN A 70 Kg MAN gm
OXYGEN	65.0	45,500	POTASSIUM	0.2	140
CARBON	18.0	12,600	SODIUM	0.15	105
HYDROGEN	10.0	7,000	CHLORINE	0.15	105
NITROGEN	3.0	2,100	MAGNESIUM	0.05	35
CALCIUM	1.5	1,050	IRON	0.006	4
PHOSPHORUS	1.0	700	COPPER	0.0002	0.1
SULPHUR	0.25	175	MANGANESE	0.00003	0.02
			IODINE	0.00004	0.03

1 A PERSON IN A DENSE CROWD RECEIVES FROM OTHERS 2mr/YEAR.

2 WRIST-WATCH LUMINOUS DIAL HAS 10^{-6} CURIE: GIVES TO CENTRAL PORTIONS OF BODY ABOUT 40 mr/YEAR.

3 AIRPLANE INSTRUMENT BOARD [WITH ABOUT 100 DIALS (LUMINOUS) EACH OF 3×10^{-6} CURIE] GIVES TO PILOT ABOUT 1,300 mr/YEAR.

4 SOME TYPICAL X-RAY EXPOSURES



EXAMINATION	SKIN DOSE mr	GONAD DOSE mr
CHEST (ANTERIOR-POSTERIOR)	160	0.36
SKULL	4,000	0.2
LUMBAR SPINE (ANTERIOR POSTERIOR)	5,200	24
FLUOROSCOPY (PER MINUTE)	2,500	7

THIS CHART IS LARGELY BASED ON:
W.F. LIBBY, *SCIENCE*, **122**, 57 (1955)

APPENDIX IV

NUCLEAR EXPLOSIONS AND THE WEATHER

The question has often been asked : What is the effect of nuclear explosions on weather ? It has been suggested, for instance, that the large amount of radioactive dust projected into the atmosphere during test explosions may have a noticeable effect on the ion contents of the atmosphere and thus exert an influence on the pattern of rainfall. The dust may also cut down to some extent the amount of solar radiation reaching the surface of the earth.

Machta and Harris[1] (of the US Weather Bureau) have considered the rather unusual weather conditions that prevailed in the US during the period 1950-53 and discussed the possible relationship between weather and the Nevada test explosions during this period. They have observed : " A number of suggested mechanisms by which atomic explosions might affect weather have been investigated and a study of climatologic data has been made to determine whether any weather anomalies exist that might be associated with atomic explosions. Although it is not possible to prove conclusively that atomic explosions have or have not influenced the weather, it is believed that this study has shown that such an effect is unlikely. The results of this study may be summarized as follows :

(1) No theoretical reason has been found for believing that any of the mechanisms examined could account for a significant change in the weather more than a few miles from the site of the explosion.

(2) The year 1953 was an unusual tornado year.

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[1] L. Machta and D.L. Harris, *Science*, **121**, 75 (1955).

Although part of the increase in the number of tornadoes reported in 1953 may have been the result of exceptionally favourable weather patterns for tornadoes, much of the increase can be attributed to improvements in the method of collecting tornado statistics.

(3) A study of temperature and precipitation records for the United States does not seem to indicate any departures from normal that are related to the atomic explosions."

Sutton[2] (Director, UK Meteorological Office) has sought to find a possible connection between the Pacific thermonuclear explosions of March 1954 and the markedly poor weather experienced during 1954 summer in the UK and Western Europe. Speaking of the difficulties in investigating such correlation between weather and thermonuclear explosions he has observed: " Weather is the first-order perturbation of climate and since the weather of 1954 did not exhibit, in the British Isles, any features that cannot be paralleled and even exceeded in past years, it follows that any effects attributable to the explosions must be of magnitude not exceeding that of ordinary weather producing influences. The detection of such additional effects, therefore, demands careful statistical analysis that cannot properly be attempted until several years have elapsed, so that existing climatic ' trends ' can be recognised and eliminated. An equally serious difficulty is that, so far, it is not known with certainty how many thermonuclear explosions occurred in 1954, or when and where they all occurred."

After discussing the various factors that could conceivably affect weather, Sutton concludes: "...the present state of meteorological knowledge renders it unlikely that a firm conclusion can be reached; but so far the available evidence points to the conclusion that recent thermonuclear trials cannot be held responsible for any world-wide extremes of weather encountered in 1954."

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[2] O.G. Sutton, *Nature*, **175**, 319 (1955).

It has aso been suggested that nitric acid formation during a nuclear detonation may be in large enough quantities to cause harmful effects. During a nuclear explosion the shock wave rapidly moving outwards heats the surrounding air and causes oxygen and nitrogen to combine to form nitrogen dioxide. It is this which apparently gives a brownish colour to the explosion cloud. Martin[3] estimates that about half a million tons of nitric acid are formed in a 20 megaton explosion. (According to AW (1950) the value will be only about a hundred thousand tons).

Nitric acid is normally produced in the atmosphere on account of decomposition of organic matter and to a lesser extent by the combination during thunderstorms of nitrogen and oxygen in the atmosphere. The acidity of normal rain (average pH about 4 to 5) indicates that the amount of nitric acid normally formed every day is of the order of a hundred thousand tons. Thus it would need a few hundred megatons explosions a year to double the nitric acid content (of the atmosphere) which is normally present.[4]

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[3] Charles Noel-Martin, *L'Heure H, a-t-elle sonné pour le monde ?*, Bernard Grasset: Paris, 1955.

[4] G.M. Dunning, "Effects of Nuclear Weapons Testing", *Scientific Monthly*, **81,** 256 (1955).

APPENDIX V

RADIOACTIVE CONTAMINATION OF FISH AND MARINE ORGANISMS

For several months following the March 1954 megatons explosions in the South Pacific Ocean (Marshall Islands) it was found that some of the fish caught at 10-20 miles off the Pacific coast of Japan were contaminated with fission products, though no significant increase in the radioactivity of coastal waters was detected. A small fraction of the fish caught showed a high level of contamination, but most of them (caught in May 1954) had an activity of about 10^{-4} microcurie per gram in the white part of the meat and about 10-100 times larger activity in the red part of the meat. The internal organs had an activity of 10^{-1} - 10^{-2} microcurie per gram. It was found that more than half of the activity was due to zinc 65. (It undergoes decay by K-electron capture, the half-life being 250 days). This was very surprising, considering that the relative abundance of zinc 65 in fission nuclides is extremely small. The concentration of this nuclide in the fish was exceedingly large in comparison to its concentration in the contaminated sea water.

It has been found — and this is an extremely important fact — that the concentration of some of the trace elements in micro-organisms is totally different from what it is in the surrounding water. For instance, vanadium exists in the oceans to a concentration of 1 part in a 1,000 million of sea water, and yet the blood of certain sea squirts can contain up to 10 percent of vanadium. This involves a 100 million-fold increase in concentration. "Such accumulation parallels the uptake of iodine by thyroid, and its specificity equals that of the best analytical reagents devised by man." It is interesting to note that brown sea-weeds can concentrate strontium upon their surfaces to the extent of 10 to 40 times its concentration in sea water: Red algae, on the other hand, can absorb practically all the ionic yttrium present.

Many of the fission products get concentrated to a remarkable degree within marine animals. Let us define ' enrichment factor ' for an element as the ratio of the amount of that element contained per gram of wet-weight of marine animals to the amount in one gram of sea water. The values of the enrichment factor for some of the fission products are given below[1]: Mo, 600 ; Ag, 2000 ; Zn, 3250 ; Cd, 450 ; Ge, >760 ; Sn, 270 ; As, 330 ; Sb, >30. Algae gave the following enrichment factors: Zn, $400-1400$; Mo, $2-15$; Sr, $8-90$.

It appears that, in general, marine micro-organisms in contaminated water accumulate the fission products, raising their radioactivity (per unit weight) about a thousand times the radioactivity of water: The radioactivity of plankton can be several thousand times that of water. The radioactivity of the micro-organisms is transmitted through food intake to macro-organisms of higher rank in food order. Apart from the food-channel, when concentration of fission products in water is rather high, fish and other macro-organisms take up these materials directly through the body surface.

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[1] R. Revelle *et al.*, "Nuclear Science and Oceanography": Paper presented at the *Geneva Conference on Atomic Energy*, 1955. (The values of enrichment factor quoted in the text are taken from this paper).

APPENDIX VI

DOSE RATES FROM SOURCES INSIDE AND OUTSIDE THE BODY

Roentgen, Rad and Rem

The unit used for expressing dose of X– and gamma radiation is the *roentgen.* Its precise definition is the following: It is the quantity of X– or gamma radiation such that the associated corpuscular emission per 0·001293 gram of air (*i.e.*, 1 cc of dry air at N.T.P.) produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign (*i.e.*, $\frac{1}{4 \cdot 80} \times 10^{10}$ ion-pairs). This corresponds to an energy absorption of about 83 ergs per gram of air and about 93 ergs per gram of tissue. Notice that in the above definition the use of roentgen is restricted to X-rays or gamma rays. It is not applicable to other ionizing agents.

For a given amount of energy absorbed in a biological material, the damage induced by an ionizing agent depends not only on the number of ions produced per unit mass of the material but also on *specific ionization*, that is, the number of ions produced per unit length of the tracks of the incident ionizing particles. For alpha rays the specific ionization is about 4,000 ions per micron of tissue.[1] For the secondary electrons which are responsible for the ionization due to gamma rays, the specific ionization is, on an average, about 20 per micron. In discussing the *relative biological effectiveness* (RBE) of different ionizing agents, it is useful to introduce the following two units: *rad* and *rem*. The rad can be called a physical unit and the rem a biological unit. The rad is precisely equal to an energy absorption of 100 ergs per gram and is applicable to all kinds of ionizing radiations. One rad produces in every cubic micron of the exposed tissue about two ionized molecules, and about the same number of excited molecules. As will be seen from the definitions of roentgen and rad, for X- and gamma rays the rad is very nearly equal to the roentgen—only about 10 percent more. Like the unit rad, the unit rem is applicable to all ionizing agents. A dose of one rem produces, by definition, for any ionizing radiation the same biological damage as would be produced by one rad of X-rays (more precisely X-rays of 200-250 kv).[2] It is thus obvious that the RBE of an ionizing agent is the ratio of the dose expressed in rems to the same dose expressed in rads. This is not the place to go into a detailed discussion of RBE and how it varies with the nature of the biological material, the criterion of damage adopted, the dose rate, and other factors. There is, generally speaking, a close relation between RBE and specific ionization. Instead of specific ionization, it is sometimes preferable to use the related concept 'linear energy transfer' (LET). It is the energy transferred to the material per unit length of track of the incident ionizing particle. A review of recent literature on the subject is given in the *Annual Review of Physiology*, 1956. Table XVIII gives the values of specific ionization in a few typical cases.[3]

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[1] One micron $= \frac{1}{1000}$ millimeter.

In experiments on rats[4] the 50 percent lethal dose

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[2] This is chosen as the point of reference as most of the observational experience relates to this range.

[3] John Furchner, *Relation Between Specific Ionization of Various Radiations and Their Relative Biological Effectiveness in Mammalian Systems*, LA-1849, USAEC (1954).

[4] E.P. Cronkite *et al.*, *Science*, **122**, 148 (1955).

(LD-50) was found to be 650 r for X-rays and 680 r for initial gamma rays emitted in an atomic explosion. This gives the RBE for atomic bomb gamma radiation to be

$$\text{RBE} = \frac{(\text{LD}-50)_{\text{X-ray}}}{(\text{LD}-50)_{\text{gamma}}} = \frac{650}{680} = 0.96$$

TABLE XVIII

Specific ionization of various radiations

Radiation		Ion pairs per micron of tissue (rough estimate)	RBE
X-ray (250 kv)	..	~ 80	1.0
Co^{60} gamma (1.33, 1.17 mev)	..	~ 10	1.0
4 mev gamma	..	~ 10	0.6
Tritium beta	..	~ 180	1.59
0.6 mev proton	..	~ 2,000	1.6
2.4 mev alpha	..	> 4,000	1.6

Table XIX is intended to serve as a guide in assessing the radiological hazard from neutrons.[5]

TABLE XIX

Neutron energy	Neutron flux per cm^2 corresponding to 1 rem
0.025 ev (thermal)	9.6×10^8
10 ev	4.8×10^8
10 kev	4.8×10^8
0.1 mev	9.6×10^7
0.5 mev	3.84×10^7
1 mev	2.88×10^7
2 mev	1.92×10^7
3 mev and higher	1.44×10^7

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[5] USAEC Release of July 11, 1955; see also "Recommendations of the International Commission on Radiological Protection (Revised Dec. 1, 1954)", *British Journal of Radiology, Supplement No. 6*, 1955.

Note also that:

1 rem = 1 rad for X- or gamma radiation
= 1 rad for beta radiation
= 0.1 rad for protons (of energy less than 10 mev)
= 0.05 rad for heavy recoil particles

In the case of thermal neutrons the only important reactions in tissues are:

$$H^1+n_0 \rightarrow H^2+\gamma+2.23 \text{ mev}$$
$$N^{14}+n_0 \rightarrow C^{14}+H^1+0.61 \text{ mev}$$

It has been estimated that the larger fraction of the biological dose is contributed by the $N^{14}(n_0,H^1)C^{14}$ process. For fast neutrons the n–p collisions constitute by far the most important mechanism for energy transfer in tissues.[6]

Energy Flux and the Roentgen

For materials consisting of light elements and for values of gamma ray energy in the region 0·08 to 2·5 mev the mass absorption coefficient μ $\left(= \frac{\text{linear absorption coefficient}}{\text{density}} = \frac{k}{\rho}\right)$ is roughly constant to about 10 percent. The value of the linear absorption coefficient in air for gamma ray photons of energy 1 mev is 3.6×10^{-5} cm^{-1}, and hence the mass absorption coefficient is $\frac{3.6\times10^{-5}}{0.001293}=0{\cdot}028 \text{ gm}^{-1}$. The energy absorbed per gm of air for an incident beam of intensity I is therefore given by 0·028 I erg/gm.

The roentgen is equivalent to an energy absorption of 83 ergs per gram, and hence the value of I for a dose of one roentgen is given by

$$\begin{aligned} 0.028\, I &= 83 \\ \text{or } I &= 3 \times 10^3 \text{ erg/cm}^2 \\ &= 2 \times 10^9 \text{ mev/cm}^2 \end{aligned}$$

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[6] B. J. Moyer, "Neutron Physics of Concern to the Biologist", *Radiation Research,* **1**, 10 (1954).

If E be the energy of the photons, a dose of 1 r corresponds to an incident beam of $\frac{2\times10^9}{E}$ photons per cm^2 where E is in mev.

Gamma Dose due to Active Deposit on Plane Surface

Consider an area (very large compared to the mean-free-path l of photons) uniformly deposited with active material emitting gamma rays. We are interested in calculating the dose at a point P at a height h above the surface.

By dividing the area into circular zones and integrating we immediately find for the total gamma ray flux at P

$$\text{Flux} = \frac{\sigma}{2}\int_h^\infty \left[exp(-kR)\right] R^{-1}dR$$
$$= -\frac{\sigma}{2}\left[Ei\,(-kh)\right]$$

where σ is total gamma ray energy emitted per unit area of the surface per second,

and k is linear absorption coefficient (including scattering) for the photons considered; $k=\mu\,\rho$

(The mean-free-path l is of the order of $\frac{1}{k}$)

If the activity of the surface is q curies per square mile (1 curie$=3{\cdot}7\times10^{10}$ disintegrations per second) and E (in mev units) is the energy of the gamma ray photons, we have

$$\sigma = 1.43\,Eq \text{ mev per cm}^2 \text{ per sec}$$

and hence the dose in roentgen per day is

$$-\frac{1.43Eq[Ei(-kh)]}{2\times2\times10^9}\times86400$$
$$\text{or } -3.09\times10^{-5}Eq\,[Ei(-kh)]$$

For fission products the average energy of the gamma ray photon is 0.7 mev and hence we have for 10^4 curies per square mile, a dose of 1 r per day at a height of about 3 feet above the surface. The variation of dose with height is expressed by the values of the exponential integral $-Ei\,(-kh)$ where $k=1.0\times 10^{-4}$ cm^{-1} $=3.0\times 10^{-3}$ ft^{-1}.

TABLE XX

h(feet)	$[-Ei\,(-kh)]$
1	5.23
3	4.14
30	1.92
100	0.91

Dose due to Natural Background Radiation

We are interested in the calculation of the dose due to (*i*) radioactive materials like uranium, thorium and potassium contained in the top layers of the earth's surface and (*ii*) radioisotopes, especially K^{40} and C^{14}, contained in the body.

If we consider an infinite homogeneous radioactive medium, then as the flux of the radiation must (by symmetry) be the same at every point of the medium, it follows that the radiation absorbed in any given element of the medium must be equal to the radiation emitted by it. Assuming that the mass absorption coefficient of radiation for the given medium is roughly the same as for the human body, we have for the dose, in rads per second:

$$\text{Dose}=W\times 1.6\times 10^{-8} \tag{1}$$

where W is the energy emitted per second per gram of the medium. W is expressed in mev.

In Table XXI the values for W are given for uranium, radium, thorium, potassium and carbon.

TABLE XXI

Element	Half-life	Energy of radiation emitted: (mev)	Total energy emitted per second per gram of material: (W mev)
Uranium (together with its disintegration products in equilibrium: U-Ra series)	4.5×10^9 yr	3.217 (gamma)	4.0×10^4 (gamma)
Ra (with products)	1.62×10^3 yr	2.327 (gamma)	8.4×10^{10} (gamma)
Thorium (together with its disintegration products in equilibrium: Th series)	1.39×10^{10} yr	2.17 (gamma)	8.9×10^3 (gamma)
Potassium 40 (180 gamma rays per minute per gram of natural potassium)	1.3×10^{10} yr	1.45 (gamma)	4.35 (gamma)
Potassium 40 (1800 beta rays per minute per gram of natural potassium)	1.3×10^9 yr	0.544 (beta, av.)	16.32 (beta)
Carbon 14 (15 beta rays per minute per gram of natural carbon)	5.6×10^3 yr	0.0668 (beta, av.)	0.0167 (beta)

The relative abundance of elements in a few cases of interest are given below:

TABLE XXII

	Abundance gm/gm			Total gamma dose:
	U	Th	K	r/yr
Granite rock ..	4×10^{-6}	13×10^{-6}	3×10^{-2}	0.102
Sedimentary rock	1×10^{-6}	3×10^{-6}	8×10^{-3}	0.026
Ocean ..	2×10^{-9}	10^{-11}	4×10^{-4}	0.0004

With the help of equation (1) and the above tables we can readily estimate the dose received by a person at the earth's surface, if we assume, as a rough approximation, that the mass absorption coefficients of rock and tissue are the same. The value obtained from equation (1) has to be divided by 2, as in this case radiation is received from only one side of the surface. The values of the dose rates so obtained are given in the last column of Table XXII.

Equation (1) can also be used for determining the dose which the body (or any specific organ) receives from radioactive elements deposited in it. In the case of beta rays, because of their short range, the body acts as an infinite medium and equation (1) holds. The same is not true of gamma rays, and in this case it may be assumed that only half the amount emitted is absorbed by the body. The values for the dose rates given in Chart IV can thus be readily obtained.

As an important illustration of equation (1) we shall derive the value of the maximum permissible total-body-burden (q) for radiostrontium which has been discussed at considerable length in the preceding chapter. Radiostrontium being a bone-seeker will be localized in the bones. For a standard man the mass of the bones is taken as 7 kilograms. The definition of the maximum permissible total-body-burden is based on the assumption that a quantity q of the given nuclide distributed in the relevant critical organ (in this case the bones) subjects it to a dose rate of 0.3 rem per week. Taking q in microcuries we thus have from equation (1)

$$\frac{0.3}{N} = \frac{q \times 3.7 \times 10^4 \times 1.6 \times 10^{-8} \times E \times 6.05 \times 10^5}{7 \times 10^3} \tag{2}$$

where E is the average energy (in mev) of beta rays from radiostrontium. (We take the average energy to be 40 percent of the maximum beta ray energy). The factor N (which is not present in equation (1) but has been inserted here) is called the non-uniform distribution factor. According to the ICRP recommendations, N is assumed to be 5 for all alpha/beta emitting nuclides which are bone-seekers. The effect of non-uniform distribution of a radioelement is to lower the value of the maximum permissible body-burden. Substituting $N=5$ in the above equation we get, in the case of strontium 89, ($E_{\max}= 1.46$ mev) for q the value 2 microcuries.

Strontium 90 is a beta emitter ($E_{\max}=0.6$ mev); its daughter yttrium 90 is also a beta emitter ($E_{\max}=2.2$ mev). As yttrium 90 has a short half-life (61 hours), there will be radioactive equilibrium in the body between strontium 90 and yttrium 90. Hence the total energy emitted per disintegration of strontium 90 is 2·8 mev. Substituting this value in equation (2), we get for q the value 1 microcurie.

Dose due to Cosmic Rays

Cosmic radiation produces at sea level about 2 ion-pairs per second per cubic centimeter of air. This, using the definition of roentgen, is equivalent to a dose of about 30 milliroentgens per year. The dose rates for higher altitudes can be readily calculated from the known variation in the intensity of cosmic rays with altitude.

APPENDIX VII

MAXIMUM PERMISSIBLE TOTAL-BODY-BURDEN (*q*) AND MAXIMUM PERMISSIBLE CONCENTRATIONS IN AIR AND WATER FOR CONTINUOUS EXPOSURE

Radioactive species	Radiation emitted	Energy of radiation emitted (mev)	Critical organ	Maximum permissible total-body-burden (*q*) microcurie	Maximum permissible concentration in air : microcurie per cc	Maximum permissible concentration in water : microcurie per cc
H^3 (HTO or T_2O)	beta$^-$	0.018 (a)	whole body	10^4	10^{-5}	0.2
C^{14} (CO_2)	beta$^-$	0.155 (a)	fat	260	10^{-5}	3×10^{-3}
Na^{24}	beta$^-$	1.39 (a)	whole body	15	2×10^{-6}	8×10^{-3}
	gamma	1.37, 2.75				
P^{32}	beta$^-$	1.701 (a)	bone	10	10^{-7}	2×10^{-4}
S^{35}	beta$^-$	0.168 (a)	skin	300	10^{-6}	5×10^{-3}
Cl^{36}	beta$^-$	0.714 (a)	whole body	230	6×10^{-7}	4×10^{-3}
Fe^{55}	(electron capture)		blood	10^3	7×10^{-7}	5×10^{-3}
	gamma					
Fe^{59}	beta$^-$	0.460, 0.257 (a)	blood	13	2×10^{-8}	10^{-4}
	gamma	1.295, 1.10				
$Sr^{90}+Y^{90}$			bone	1	2×10^{-10}	8×10^{-7}
(*i*) Sr^{90}	beta$^-$	0.61 (a)				
(*ii*) Y^{90}	beta$^-$	2.2 (a)				
I^{131}	beta$^-$	0.608, 0.335 and others (a)	thyroid	0 6	6×10^{-9}	6×10^{-5}
	gamma	0.364, 0.638 and others				
Ra^{226}	alpha	4.777	bone	0·1	8×10^{-12}	4×10^{-8}
	gamma	0.186				
Pu^{239}	alpha	5.15				
	gamma	0.053, 0.100 and others				
(soluble)			bone	0·04	2×10^{-12}	6×10^{-6}
(insoluble)			lungs	0·02	2×10^{-12}	
Any mixture of alpha emitters					5×10^{-12}	10^{-7}
Any fission mixture (beta, gamma)					10^{-9}	10^{-7}

(a) The figures refer to the maximum beta ray energy.

(Based on the Recommendations of the International Commission on Radiological Protection, 1954).

CHAPTER VI

GENETIC EFFECTS OF NUCLEAR EXPLOSIONS

In this chapter we shall deal with the effects of nuclear explosions on the genetics of man. This is a grave and profound question. The entire subject of the genetic effects in living organisms induced by nuclear and other ionizing radiations is replete with many complications and difficulties. However, if we keep to the barest essentials—as we propose to do here—a reasonably clear (though at times crude, for lack of space) presentation is not too difficult.[1]

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[1] Amongst the many papers and reviews that have recently appeared, special mention should be made of the following lucid and authoritative presentations:

(1) H. J. Muller, "How Radiation Changes the Genetic Constitution", *Bulletin of the Atomic Scientists*, **11,** 329 (1955).
(2) M. Westergaard, "Man's Responsibility to his Genetic Heritage", *Bulletin of the Atomic Scientists*, **11,** 318 (1955).
(3) J.B.S. Haldane, "The Genetic Effects of Atomic Bomb Explosions", *Current Science*, **24,** 399 (1955).
(4) H.M. Slatis, "Current Status of Information on the Induction of Mutations by Irradiation", *Science*, **121**, 817(1955).

It is a curious commentary on our times that Muller's paper—it should be noted that the profound epoch-making discovery of the induction of mutations by ionizing radiation is due to Muller in 1927—originally prepared for the Geneva Conference on the Peaceful Uses of Atomic Energy (August 1955) could not be presented and discussed at the Conference. As *Science* [**122**, 813 (1955)] observed in its editorial (on 'H.J. Muller and the Geneva Conference'), "it is tremendously important at this time that there be free and open discussion of all possible radiation dangers. Only in this way can maximum progress be made in evaluating the dangers and taking necessary steps to reduce or eliminate them. There is

The general conclusion emerging from the discussion to follow is that *ionizing radiation induces deleterious genetic effects no matter how small the radiation dose is*, but it is unlikely—though not yet firmly established—that the global dose resulting from test explosions so far conducted will give rise to *noticeable* genetic consequences: To do so the number of (high-yield) explosions would have to be about 5-10 times larger.

Chromosomes and Genes

For a proper appreciation of the considerations on which this very important conclusion rests, it is necessary to digress somewhat and describe in the broadest outlines some of the basic facts about *chromosomes*, *genes* and *mutations*.

Every living organism starts its individual life as a single cell. Take, for instance, the case of man. When he (or she) first sees the light of day, he is already a colossal organization of cells, containing very roughly 10 million million cells. But about 40 weeks before this event it was just a single cell—a hundredth of an inch in size—derived from the fusion of the sperm (male germ cell from the father) with the ovum (female germ cell

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no magic formula for arriving at a figure for the so-called 'permissible dose'. In Handbook 52 of the US National Bureau of Standards, in which this term is defined and its origin reviewed, it is made clear that this dosage—0.3 roentgen units of X-rays per week for whole-body irradiation—should be permitted only for adults exposed in small numbers. For children or large populations, it is recommended that the usual value be divided by 10. With the prospects of a great increase in peacetime use of atomic energy, we cannot too soon know what are the reasonable upper limits of radiation where large numbers of persons are involved. Important precedents are being established, and it will become increasingly costly and difficult to modify them if they should prove to be inadequate.

"There are therefore compelling practical reasons, to be added to the obvious ones that should apply at all times to all forms of knowledge, for resisting any authoritarian or arbitrary suppression of free and open discussion of the hazards to man of radiation."

from the mother). The fertilized ovum—the single cell which is the beginning of the individual—contains 24 pairs (all the pairs are different from one another) of microscopic thread-like things called chromosomes.[2] (The number of chromosomes contained in a cell is characteristic for each species: It is 48 in man, 40 in mouse, 8 in *Drosophila melanogaster* (fruit-fly), 20 in maize plant and so on). One member of the pair comes from the sperm and the other member from the ovum: The members of the pair are called *homologous* chromosomes. Out of these 24 pairs, in 23 the partner chromosomes are alike. In the case of the remaining pair—called the pair of *sex chromosomes*—the partner chromosomes are alike for a female individual but unlike for the male individual.[3] The female pair is represented as (X, X) and the male pair (X, Y). The chromosomes other than the sex chromosomes are called *autosomes*: The sex chromosomes are sometimes called *allersomes*.

Let us now for a moment go back to the fertilized ovum (*zygote*). It begins to divide and at the end of a day or so the first division (*mitosis*) takes place giving two daughter cells, each having its full complement of 48 chromosomes identical with the 48 chromosomes in the original fertilized ovum—a division is a duplication of chromosomes. The two daughter cells further divide, and so on and on the process continues till at the end of about 40 weeks (when the child is born) there are roughly 10 million million cells representing, on an average, something like the 43rd generation of the original zygote. These cells undergo some further divisions in the subsequent life of the individual, thus making a total of about 50 generations during the entire life. During all this process, but for one exception to be mentioned presently, the chromosome content of these millions upon millions of cells is exactly identical with that of the zygote which was the starting point of the individual. The exceptions are the *germ cells*—sperms in a male and ova in a female. (Changes in chromosomes called mutations are discussed later). These are produced as a result of cell division without duplication of chromosomes, that is, *reduction division* or *meiosis* as it is called. The 24 pairs of chromosomes in the parent cell divide into 2 sets—one member of each pair going into one set—and hence in a reduction division the two daughter cells (germ cells or *gametes*) have only one set of 24 chromosomes each.[4] The number of ways in which this distribution into two sets can occur is extremely large. As each chromosome in a set can be obtained in two ways (corresponding to the two members of a pair of homologous chromosomes), there are altogether 2^{24}, that is, about ten million different ways in which the distribution can take place. In every germ cell some chromosomes belong to the mother's side of the original fertilized ovum (zygote) and some to its father's side, but in different germ cells—all arising eventually from the same fertilized ovum—these are mixed up in different ways, there being ten million ways, as we have seen.[5]

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[2] We are not considering here the case of *parthenogenesis*, that is, reproduction without fertilization (*syngamy*) which occurs in some insects and plants. A male bee (drone) is produced parthenogenetically. It contains only the set of chromosomes derived from the mother (bee queen); the set from the father is missing as the drone has no father. Drone is a *haploid*. Man is a *diploid*, because he has two sets of chromosomes, the 'mother-set' and the 'father-set'.

[3] This is so for all mammals. In birds and some insects the situation is reversed.

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[4] This is an extremely simple version of the process. In some greater detail and taking the case of a male (about which much more is known) a *spermatogonium* (diploid cell) develops into primary *spermatocyte* which undergoes reduction division into two secondary spermatocytes (haploids). Each of these two by ordinary division (mitosis) forms two daughter cells giving in all four *spermatids* which mature into *spermatozoa* (sperms). Mature germ cells—egg or sperm—are called gametes.

We now ask the question : How does a fertilized ovum at the start of its unique career of marvellous growth and development (*ontogenesis*) 'know' that it is to grow into a human being—and that it is some particular Mr. A or Miss B, different from every other human being alive or dead or to be born in the future? Why does not a human zygote ever grow into a monkey or a mango tree? In other words how is 'information' about cell's inheritance—man or monkey or whatever it may be—indelibly stored or engraved in the cell? It is hardly necessary to say that, as yet, not even a nearly complete answer to this great riddle of life is available. However, the broad elements of the situation can now be understood in terms of the chromosome-gene concept. As Westergaard has observed : "Some day it will probably be realized that one of the most important achievements of this century has been the formulation of the modern theory of biological inheritance, known as the 'gene-chromosome theory'. For it will be seen that this theory has revolutionized not only the biological sciences, but also technology, medicine, and even the humanities.

"Biology has been revolutionized because a fundamental biological problem, that of the mechanism of organic evolution, can now for the first time be seen from a sound, scientific point of view."

Genes are chromosome-parts : Each chromosome has a thousand or so of genes. (A human cell has about 20,000 genes, if not more). They lie along a chromosome in a linear sequence, like beads on a string. Genes are extremely stable gigantic chemical molecules (built from four nucleotides) containing about a million atoms each.

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[5] In a lifetime a man produces very roughly 10^{12} sperms and a woman 5×10^2 ova.

Genes are the material carriers of definite hereditary features (anatomical, physiological and psychological); they between them determine all our inherited and inborn *characters*. It is apparent from what has been said above about chromosomes that in the body of an individual all somatic cells, that is, all cells other than germ cells, have an identical gene content—identical with the gene content of the fertilized ovum (zygote) which was the first beginning of the individual. The case is quite different with germ cells. The genes in them are of course identical, though only half in number, with those in the original zygote.[6] However, as the number of possibilities in which (2x24) chromosomes distribute themselves into two equal sets in meiosis is extremely large, the chance that any two germ cells in an individual have identical genes is negligibly small.

"Genes determine whether we belong to blood group A or O, whether we are born with normal vision or afflicted with one of the various types of hereditary blindness, whether we have brown, blue or hazel eyes, whether on a rich diet we grow fat or remain slim, whether musical education makes virtuosi of us or leaves us unable to distinguish one tune from another, and so on through the thousands of details which together make up our physical and mental personalities." [7]

The genes fix, as it were, the broad framework—the upper and lower bounds—within which the expression of hereditary characters in the individual takes place. Within these broad limits the actual manifestation will depend upon the nature of environment to which the individual is subjected. What the individual becomes is an integration of the *genotype* and the environment—nature and nurture—, but the genotype fixes within quite narrow and rigid limits as to what the actual manifestation can be. Often one gene exerts its influence on more than one *character*—this is called *pleiotropy*. Also a particular character is often determined by the combined influence of many genes.

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[6] This is so except in the very rare event of mutations described later.

[7] C. Auerbach, *Genetics in the Atomic Age*, (Oliver and Boyd: London, 1956).

We have seen that somatic cells in an individual carry 2 sets of chromosomes—one derived from the mother and the other from the father—and every chromosome in one set has its partner, its homologue, in the other set. Further, to every gene in a chromosome there is normally present its counterpart or *allele* at the corresponding position or *locus* in the homologous chromosome. An allele is an alternative form of the same gene: A gene and its allele control the same *hereditary feature* or *character* in the individual. A body cell carries, therefore, a double set of genes. There is, however, an important exception to this. The X chromosome (being longer than the Y chromosome) carries some genes which do not have their alleles in the Y chromosome. These genes are called *sex linked genes*, and they play a particularly important role in studies in genetics.

If, in an individual, a particular gene and its counterpart on the homologous chromosome, that is, the two alleles (in homologous chromosomes) of the given gene—and this is a more convenient way of speaking— are identical, the individual is said to be *homozygous* with respect to the given gene. An individual is said to be *heterozygous* with respect to a given gene if the two alleles are not identical. Some genes have more than two alleles (*e.g.*, the gene which determines the main blood groups has three alleles).

At this stage we can introduce the concept of *dominant* and *recessive* genes (or rather alleles of genes). Take, as an example, the case of the gene responsible for the colour of our eyes. Consider the two alleles of this gene, one corresponding to blue eyes and the other to brown eyes. If a person has inherited one allele for blue eyes and the other allele for brown eyes, the colour of his eyes is not a compromise between blue and brown, but he has brown eyes. The allele for brown eyes suppresses the mainfestation of expression of the allele for blue eyes. The brown-eyes allele is called *dominant allele* and the blue-eyes allele is called *recessive allele.* It is usual to represent a dominant allele of a given gene by a capital letter (B for brown-eyes allele) and a recessive allele by a small letter (b for blue-eyes allele). A recessive allele cannot express itself in the presence of a dominant allele[8]. Thus it is only an individual in which both the alleles for eye colour are *b* alleles—we write (b, b) for short—that has blue eyes. (B, B) and also (B, b) individuals have brown eyes. It is important to note that though (B, B) and (B, b) are genetically different, yet as regards eye colour their appearance (that is, *phenotype*) is similar. (Another interesting example is of straight and curly hair gene : The allele for curly hair is

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[8] A sex linked gene, even if recessive, when present in a male will always be able to express itself as its counterpart will be missing in the Y chromosome. In the case of a female a recessive gene in an X chromosome will be unable to express itself if the other X chromosome carries its dominant allele. A character controlled by a sex linked gene is spoken of as a *sex linked character.* In human beings colour blindness and haemophilia (bleeding disease) are the best known examples of sex linked characters.

The main blood group genes A, B and O provide an instructive example of autosomal genes—genes carried on chromosomes other than the sex chromosomes. (Study of blood groups has probably contributed more than anything else to our basic knowledge of human genetics). The alleles and corresponding blood groups are shown below :

Alleles	..	AA	BB	OO	AO	BO	AB
Blood group	..	A	B	O	A	B	AB

The alleles A and B are dominant with respect to the allele O. A and B are equal in strength; neither of them dominates over the other.

dominant). A genotype determines the phenotype, but not *vice versa.*[9]

We have just spoken of dominant and recessive alleles; but, in general, the dominance of an allele is never complete. Generally speaking, a recessive allele, and particularly if it is a deleterious one, when present in an individual carrying its dominant counterpart, does produce a small but not altogether negligible effect: Its expression is not completely suppressed. This is of considerable importance in relation to mutations which we now consider.

Mutations

Genes, as we have said before, are extremely stable, passing on unchanged from one generation to another. Occasionally—though very rarely—they undergo a spontaneous (molecular) change or modification giving rise to a new allele of the original gene. This is called *spontaneous* or *natural mutation.* A mutated gene, the new allele, is as stable as the original gene and passes on unchanged from generation to generation till it (in its turn) suffers a mutation or becomes extinct because of the individuals carrying it dying prematurely or failing to reproduce. The chance that a human gene in one generation undergoes a natural mutation, that is, mutation arising from natural causes and not under the influence of an artificial modification of the natural environment, is about one in a hundred thousand (for some of the genes). This is based on direct statistical observations. The estimates so far available of natural mutations in man relate to an extremely small number of genes (about 15 or so out of a total of over 10,000) which control some easily recognizable hereditary disease (*e.g.*, the bleeding disease 'haemophilia') or body deformity (*e.g.*, 'chondrodystrophic dwarfism' — developmental disorder of growth leading to shortness of arms and legs). The disease (or deformity) caused by a spontaneous mutation appears in the offspring of ' normal ' individuals, and passes on to the descendants of afflicted individuals in accordance with the (Mendelian) laws of inheritance. We give below a few typical examples.[10]

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[9] Notice that the mating of two brown-eyed individuals (B,b) and (B,b) can result in blue-eyed (b,b) offspring, the relative figures of (B,B), (B,b) and (b,b) offspring being respectively 1/4, 1/2 and 1/4. This means that on an average there will be one blue-eyed child for three brown-eyed children. Notice that the offspring show gene combinations not present in the parents.

If we assume that a human gene, on an average, has 2 alleles, then as there are at least 10,000 genes, the number of possible human genotypes equals the more-than-astronomical figure of 10^{3000}. (The total number of atoms in the Universe, in comparison to this figure, is infinitesimal). A very large number of these genotypes will obviously be not viable. It is apparent why no two human beings (dead, alive or to be born) are ever likely to have the same genotype (with the exception of identical twins)—and also, as a little reflection shows, the same phenotype.

TABLE XXIII

	Natural mutation rate per generation for the gene responsible for the disease	
Haemophilia (This is due to sex linked recessive gene)	2.0×10^{-5}	(Haldane, 1935)
Achondroplasia (This is due to dominant gene)	4.5×10^{-5}	(Morch, 1941)
Infantile amaurotic idiocy† (This is due to recessive gene)	1.1×10^{-5}	(Neel, 1949)

† Progressive mental deterioration and blindness.

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[10] See J.V. Neel and W.J. Schull, *Human Heredity*, University of Chicago Press, 1954 ; also Medical Research Council (UK), *The Hazards to Man of Nuclear and Allied Radiations*, H.M.S.O. (London), 1956.

(It is indeed a most remarkable thing that mutation rates for such widely different diseases as haemophilia and congenital idiocy should be the same: It is in a way a convincing demonstration of the fundamental nature of the gene theory).

It is estimated that for the large majority of genes the chance of mutation is probably much less, maybe 10-100 times less. (We shall use the letter u to denote the natural mutation rate per generation: $u \sim 10^{-5}$).

The rate of natural mutation per gene per generation is of the same order—though somewhat less, about half—in *Drosophila* and mice as in man. (The duration of human generation is more than a thousand times that of *Drosophila* generation). This is one of the most striking facts in genetics.

It is necessary to state here explicitly that though mutations[11] occur in all cells of the body—somatic cells and germ cells—it is only mutations in germ cells (and gonad cells which on meiosis produce germ cells) which are relevant here. Mutations are extremely rare events, and hence the proportion of somatic cells carrying a mutated gene in comparison to the number of cells carrying the original (unmutated) gene will be negligibly small, and thus (in general) without any effect on the individual.[12] On the other hand, a germ cell carrying a mutated gene, if it chanced to participate in fertilization (syngamy), will lead to *all* the cells in the body of the offspring to contain the mutated gene. In consequence the mutated gene, even if recessive, will find some expression in the offspring (arising from the germ cell carrying the mutated gene).

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[11] By mutation we here mean only what are technically called 'point mutations'. We shall not concern ourselves with the much less frequent chromosome aberrations, *i.e.*, breaks, inversions and translocations in the structure of chromosomes.

[12] In certain rare cases, even mutation of the somatic cells may have some genetic consequences. This will happen if in a very early stage of an embryo, there occurred a mutation in one of the cells. Both the normal and the mutated cells will multiply to build up the individual. He would genetically be of *mosaic* nature—certain portions of his body carrying the characteristics of the mutated gene. If the mutant were a dominant, then the mosaic nature of the individual may be directly observable. (This phenomenon of early somatic mutation has been observed in various mammals). Further, in

Induced Mutations

It is now recognized (beginning with the great work of H.J. Muller in 1927)—and it is one of the most fundamental and well-established of biological principles—that genes in every living organism when exposed to ionizing radiation can, and do, undergo mutations. These are called (radiation) *induced mutations*, to distinguish them from natural mutations.[13] The number

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some cases of such mosaic individuals, cells descended from the original mutant cell contribute to the germ cell tissue of the gonads of the individual. Some of the offspring of these mosaic individuals will inherit the mutant gene.

Mosaic in animals is what is called bud sport in plants. In the case of fruits, bud sports have often led to new market varieties.

(See for instance, Curt Stern, *Principles of Human Genetics*, Freeman and Company: San Francisco, 1950).

[13] The rate of mutation can also be influenced by an alteration in the temperature of an animal (within its normal viability range) and by chemical means. Thus it has been demonstrated that in *Drosophila melanogaster* a rise of temperature of 10 deg.C more than doubles the spontaneous mutation rate. In 1942 Auerbach and collaborators established that chemical agents could bring about mutagenesis, the first to be discovered being mustard gas $(ClCH_2CH_2)_2S$. Many chemical mutagens (radiomimetic chemicals) are now known, e.g., nitrogen mustards, di-epoxides. (It may be remarked that, crudely speaking, the amount of a chemical mutagen required to produce the same effect as a given dose of radiation is such that the number of molecules of the chemical mutagen per cubic micron of tissue in the former case is equal to the number of ions per cubic micron in the latter case). The extent and degree of similarity between the effects produced by chemical mutagens and radiation is indeed very striking. In points of detail there are significant differences. Chemical mutagens in comparison to radiation

of mutations caused by an exposure to X-rays and gamma rays (and also beta rays) is directly proportional to the total quantity of dose received—the dose measured in roentgen units.[14] (For heavy ionizing particles the mutation rate is proportional to about $\frac{3}{2}$th power of the dose in *rads*). Induced mutations, leaving aside points of relatively minor details, are similar to natural mutations. The rate of induced mutations in man is not *directly* known.[15] In fact it has so far been experimentally

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induce a much higher proportion of mosaics. It has also recently been established that chemical mutagens can induce mutations in genes which are entirely stable to radiation.

[14] The radiation-sensitivity to mutation of germ cells varies with the stage of development of the cell. Thus in *Drosophila* the spermatids are roughly ten times more sensitive than spermatogonia. The mature sperms fall in-between in sensitivity. This result if applicable to man is of considerable significance. In man the period spent by germ cells in mature (or nearly so) state is only a few months as compared to about twenty five years spent in the early stages.

It may be mentioned that the rate of radiation-induced mutation in experimental animals can be modified to some extent by administration of suitable chemicals and also by change in oxygen-tension. This has a similarity to the effect of chemicals on radiation response described on page 91. Probably the basic cause is the same in the two cases as it is believed that somatic effects, in general, are a consequence of mutations (chromosome aberrations) produced in somatic cells.

The law of exact proportionality between number of induced mutations and dose of radiation probably breaks down when the *dose rates* are excessively large, e.g., of the order of a few thousand roentgens per minute. [See A.M. Clark, *Nature*, **177**, 787 (1956)].

[15] "Two attempts have been made to measure directly the effects on man himself—on survivors of the atomic bombs in Hiroshima and Nagasaki, and on radiologists in the United States of America. Only a preliminary report of the Japanese study is available, covering some 2,000 births. No strong indication was found of any effect on the sex ratio, the malformation rate, the stillbirth rate, or the birth weights of the children of whom at least one parent had developed one or more of the cardinal symptoms of radiation injury in the months after the bombing. The survey on American radio-

determined in only two animals* (one insect and one mammal), the classic case being that of the small fruit-fly *Drosophila.* Recently it has been studied in mice[16], and the best that can be done under existing knowledge is to *assume* the 'mice-value' to apply to man. For some genes in mice the (average) chance (probability) for an induced mutation to occur is—as obtained experimentally with about 100,000 mice—one in four millions for a dose of one roentgen.[17] (In *Drosophila* the observed rate of

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logists was made by a routine postal questionary to over 3,500 of them, and the same questionary was sent to a similar number of physicians in other specialties. As so often happens with postal questionaries, the replies were far from complete. About three-quarters of the radiologists, but only about half of the other physicians, responded. No significant difference in the number of foetal deaths in the two groups was found, but there was a small and significant increase in the number of congenital malformations among the children of the radiologists (5.99% of 5,461 children born to radiologists, as compared with 4.84% of 4,484 children born to the controls). But there is ample room for bias in the incomplete response to the questionary, and it cannot be assumed that this small difference is due to irradiation.

"The authors of both surveys are nevertheless careful to make the point that their inconclusive results should not be interpreted as indicating that the genetic effects of radiation in man are small. Animal experiments have shown that the great majority of mutations, whether occurring naturally or following artificial radiation, are at least partially recessive and so unlikely to be detected in the first generation after exposure. Perhaps the effects most likely to be detected in the first generation are not stillbirths and congenital malformations, but a reduction in adult body size and in average length of life. These would require a longer follow-up for their detection." [*British Medical Journal,* July 9, 1955, p. 113].

* It has also been measured in a couple of plants, *e.g.*, Indian corn.

[16] W.L. Russell, "X-ray Induced Mutations in Mice", *Cold Spring Harbor Symposia Quant. Biol.* **16**, 327 (1952).

[17] Russell's value relates to the irradiation of spermatogonia of mice. The mice were homozygous for seven dominant genes and were mated to unexposed recessive females. Mutations were found in six of the above seven genes.

induced mutations is about one-tenth of that in mice). The probability of induced mutation is not the same for all genes, and it is possible (though at present it is a surmise only) that some genes in mice have a mutation probability as low as one-tenth of the above value, whereas some other genes have a ten times larger value. (We shall use the symbol v for the rate of induced mutations per unit dose (1 roentgen): $v \sim 2.5 \times 10^{-7}$).

Most induced mutations are largely recessive. Muller in experiments with *Drosophila* found—to quote a typical example—that among 1,000 fruit flies born of parents exposed to an X-ray dose of 150 roentgens, mutations occurred as under:

Total number of flies	1000
Number of flies which showed mutation	156 or 15.6 percent of total

The types of mutations (shown by the 156 flies) were distributed as follows:

Type of Mutation	*Percent of total showing mutation*
1. Detrimental recessive (harmful to the individual but without visible effect)	64
2. Recessive lethal (individual viable but fitness reduced)*	16
3. Dominant lethal (individual carrying it not viable)	16
4. Recessive visible (individual 'normal' but the homozygous descendant morphologically different from 'normal' type)	3
5. Dominant visible (individual morphologically different from 'normal' type)	1
	100

It is believed that the pattern of induced mutations in man would, roughly speaking, be similar to this.

Doubling Dose

If we take for a gene the probability of induced mutation to be 1 in 4 million for a dose of 1 roentgen, then for a dose of 40 roentgens it is 1 in 100,000 which is also the probability of natural mutation in one generation. Th dose of 40 roentgens is spoken of as the *doubling dose*, as it is the quantity of radiation which when received by an individual (what is relevant is the dose received by the reproductive organs) raises the total mutation probability (per gene), that is, the sum of the probabilities for natural and induced mutations in a gene, to double the natural value. If we denote the doubling dose by D, we have

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*The homozygous descendant will not be viable.

$$D = \frac{u}{v} \text{ (roentgen)} \qquad (1)$$

It is hardly necessary to add that the above estimate of the doubling dose—the actual value is likely to vary to some extent from gene to gene or groups of genes—is to be taken as only indicating the likely order of magnitude: It involves considerable uncertainty because of the indefiniteness in our present knowledge of natural and induced mutation rates in man. It is, therefore, of considerable importance to observe that on the basis of general considerations, quite independent of any definite knowledge of the natural and induced mutation rates, it is possible to fix unambiguously for the doubling dose a 'lower ceiling', as it were, below which the actual value (whatever it may be) could not possibly go[18]. Spontaneous mutations are induced by a variety of natural causes including the natural background ionizing radiation (due to radioactive substances normally present within the human body and the environment, and cosmic rays). At the end of Chapter V we estimated the total whole-body dose from exposure to natural background radiation up to the age of 30-40 years (when reproduction ceases for most people) to be about 4 roentgens. The dose received by the reproductive organs (gonads) would be somewhat less because of the shielding provided by the body-parts: The gonad dose will be about 3 roentgens. If an individual is exposed to a further gonad dose of 3 roentgens from 'artificial sources', *e.g.*, fallout from nuclear explosions, he will undergo (on an average) as many more gene mutations as the number caused by the 'natural dose' of 3 roentgens. Now the natural dose of 3 roentgens produces only a fraction of the total number of natural mutations, as there are, besides radiation, other influences—thermal and chemical—which contribute their share to the total number of natural mutations. Thus, to induce mutations equal in number to the natural mutations a gonad dose exceeding 3 roentgens (or a body dose exceeding 4 roentgens) would be necessary: In other words 3 *roentgens is the lower ceiling to the doubling dose* (for gonads). (If it be assumed, following Haldane, that in man, and possibly in other long-lived animals, natural mutations are almost all caused by the background radiation, then the doubling dose is equal to 3 roentgens).

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[18] There are no arguments of comparable validity for fixing the 'upper ceiling' but from what we have said about the uncertainties in the values of u and v, it is extremely unlikely that it would exceed 400 r; possibly it is much less. However, for assessing an upper limit to possible genetic hazards of global fallout from nuclear explosions, it is the *lower ceiling* for D which is relevant.

Gene mutations are almost always detrimental to life. Mutations occur at random, and mutated genes, that is, genes that have undergone natural or induced mutation, almost invariably exert a deleterious effect on the individual carrying them: A harmless mutated gene is an exception, and a beneficial mutation is a rarer exception still. Because of the very long time periods involved over which natural mutations have been taking place all the while, it is likely that pratically every possible mutation has occurred many times over. The beneficial mutations—though exceedingly rare— because of the advantages they confer on the individuals carrying them, tend to be perpetuated, whereas detrimental mutations tend to die out as their effect is to reduce the fertility and fitness of their carriers. Thus in course of time every species comes to acquire a set of genes that is best for it in relation to its environment. It is, as it were, in equilibrium with its environment, and hence any change in its gene composition, any mutations, would displace it away from equilibrium and would thus be disadvantageous to the species.[19] This in a sense is the crux of the whole situation.[20]

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[19] Mutation is always 'contemporaneously' disadvantageous to a species, but it is necessary if the species is to survive the change in environment over geological periods. The mutation rate should not therefore be too low; and in fact the process of natural selection selects, as it were, genes that have an appropriate mutation rate. It can be seen that for *organic evolution* to take place mutation rate should satisfy the following two conditions:

$$un_1 > 1$$

$$\text{and} \quad uN < 1$$

where n_1 is the number of generations in, say, 10^8 years over which evolution has taken place and N is the number of genes in the cell. The condition $uN \sim 1$ arises from the fact that if the total number of mutations in a cell is more than one —as deleterious mutations are more likely than beneficial ones— the effect of a beneficial mutation is likely to be lost.

If we combine the two relations into

$$u^2 \sim \frac{1}{n_1 N}$$

we have, taking $N \sim 10{,}000$ and $n_1 = 3 \times 10^6$, $u \sim 10^{-5}$.

[20] It should be mentioned, however, that induced mutations can be used to a great advantage under special conditions (*e.g.*, plant breeding) where it becomes possible to select the very rare 'beneficial mutation' — 'beneficial' here means, of course, profitable from the point of view of the breeder (man)—and eliminate the overwhelmingly large number of carriers carrying deleterious mutations. For instance, radiation-induced mutations in penicillium mould have made it possible to increase the penicillium yield a thousand-fold. Mention may also be made of the recent Swedish work on the induction of "beneficial mutations in barley." "The spontaneous mutation rate is so low that time, labour, and experimental area required for the collection of positive mutations naturally arisen, would be unreasonably great. Since, by the application of ionizing raditions,

Most mutations are recessive and the harm done to the individual by a mutated gene is often slight, and is biochemical and physiological (and/or psychological) in nature. It very rarely manifests itself as a deformity (or 'monstrosity') in the external appearance of the individual. Nonetheless, the deleterious effect of a mutated gene is (always) there in causing one or more functional impairments and in a reduction in the over-all fitness and health of the individual—*a mutation is almost always detrimental to life, development and reproduction.*

" Even a slightly harmful mutation does an amount of harm comparable in the end to that done by an extremely harmful one. This is because the number of descendants to which any given mutant gene is transmitted before it causes extinction of its line of descent tends to vary inversely with the amount of harm it does. That is, it makes up for doing less harm to each individual and thereby harms the population about as much in the end. We all suffer from an accumulation of several or many so-called mutations."[21]

The presence of a mutated gene in an individual almost invariably increases to some slight extent his or her risk of failure to reproduce or of premature death, and as a consequence of it reduces the chance of passing on the mutated gene to the individual's progeny. We shall denote by the letter p the probability that an individual carrying a mutated gene fails to reproduce or dies prematurely (before attaining the age of puberty). It is, therefore, also the probability of the mutated gene ceas-

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the mutation rate can be raised several thousand times, such a collection is now made possible and can be adopted as part of the breeding routine, without any special expansion of ordinary experimental stations." (See L. Ehrenberg *et al.*, " The Production of Beneficial New Hereditary Traits by Means of Ionizing Radiation", paper presented at the *Geneva Conference on Atomic Energy*, 1955).

[21] H.J. Muller, *Journal of Heredity*, **XLVI**, 199 (1955).

ing to pass on to the next generation: To use Muller's phrase, p is the probability of genetic death or genetic extinction. The value of p varies from a few percent to a small fraction of one percent, depending on the mutated gene. According to some estimates, 2.5 per cent ($p=\frac{1}{40}$) represents a reasonable average value. (In other words, it takes on an average about 40 generations before a deleterious mutant is eliminated). We readily see that in a situation of equilibrium the number of new mutations must equal the number of extinctions of mutated genes, that is,

$$uN=pf \tag{2}$$

where N is the number of 'normal' genes in a germ cell, f the number of mutated genes and u, as before, is the probability of spontaneous mutation per gene per generation.

Substituting in the above relation $N=10^4$, $u=10^{-5}$ and $p=\frac{1}{40}$ we have, for the natural mutation load that a germ cell carries:

$$f=\frac{uN}{p}=4$$

A doubling of the mutation rate, if continued over centuries, would lead to a doubling of the genetic load f.

Mutations are largely recessive. The average chance of the occurrence of a hereditary abnormality due to the same mutated gene being present in the two homologous chromosomes of an individual is

$$N\,(f/N)^2=N\,(u/p)^2 \sim 16\times 10^{-4},$$

that is, 0.2 percent.

Genetic Hazard from Test Explosions

It is extremely difficult, in fact not possible, because of the many uncertainties involved to make a reliable estimate of the gene mutations induced in the world population as a result of fallout from test explosions. If we assume that one nominal high-yield fission explosion (energy equivalent to 20 million tons of TNT) subjects everyone in the world to a dose of 1 milliroentgen—an underestimate by a considerable factor—it amounts to a world dose of about 2.5 million man-roentgens. If we further assume that Russell's value for induced mutations in mice applies to man, a dose of 2.5 million man-roentgens will induce in this world population $(2.5\times10^{6}\times2.5\times10^{-7})N$ mutations, where N is the number of genes in a human germ cell ($N \sim 10{,}000$), that is, 6,000 mutations. About 2,000 would be lethal and 4,000 deleterious (but not lethal) mutations, and as practically all of them are recessive, the number of deaths (assuming a steady world population) due to global fallout from one megatons test explosion is expected to be, on the minimum, about 1,000 : These deaths would be spread over a large number of generations. In addition to these deaths detrimental mutations would be present in about four times this number of people.

The number of mutated genes naturally occurring in the human population is the number (f) of mutated genes per person multiplied by the world population, that is, it is about ten thousand million mutations. It would thus require an average dose of about 1,500 roentgens per person (or 4×10^{12} man-roentgens for the total population) to double the number of mutated genes in the existing population. Such a large exposure could only arise in an all-out nuclear war. In a nuclear war, the world population would be subjected to a dose running into *thousands of millions of man-roentgens* with extremely serious *genetic consequences*—and this is, of course, in addition to the terrific devastation and damage directly inflicted on the population.[22]

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[22] " Apart from producing long-term genetical sequelae in man, radiation is capable of a similar action upon the mechanism of heredity in other animals, and in plants. Inparticular, 'Espinasse (*Manchester Guardian*, March 31, 1955) has drawn attention to the possible effects of radiation upon symbiotic and parasitic organisms. Numerous species live together in balanced and commensal relationships which have become mutually adjusted over long periods of selection.

We now ask the question: What burden of mutations (in addition to the natural burden) can mankind carry without suffering any noticeable damage? "Muller thinks that a doubling of the spontaneous mutation rate in man would be catastrophic, but he thinks that a 10 percent increase may be tolerated."[23]

Slatis[24], on the other hand, has observed: "What would happen to man if the mutation rate were permanently doubled by an accidental poisoning of the atmosphere by irradiation? It would be several generations before the accumulation of new mutations would amount to very much. The average number of deleterious mutations would increase, and the frequency with which persons bearing the same mutants would marry and have defective offspring would increase too. For completely recessive genes, the doubling of the mutation rate means that the frequency of the gene and

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Many bacteria and protozoa, for example, do little harm to the hosts in which they live, and may, on the contrary, subserve a vital function through the synthesis of nutritional factors essential to the host. However, mutation in a population of such symbiotic organisms could certainly involve serious consequences for the host organism. 'Espinasse is not clear on what grounds a responsible scientist could write off any such possibility, arising from increased background radiation, as negligible. In the writer's opinion the possibility might well be remote, from the high and often extreme natural radioresistance which many unicellular organisms frequently possess. Nevertheless, it is not entirely to be dismissed, when we consider the vast range of species, from viruses upwards, and the astronomical number of cells, likely to be exposed. Since the hereditary mechanism of many micro-organisms is asexual, in these cases any mutation would not be masked by the presence of a normal " allelomorph " derived from a second parent, but might be expressed in all the descendants of the mutated individual." [Alexander Haddow, "The Problem Before Mankind," *The Bomb : Challenge and Answer,* edited by Gilbert McAllister, 1955].

[23] See M. Westergaard (*loc. cit.*)

[24] H.M. Slatis, 'Current Status of Information on the Induction of Mutations by Irradiation', *Science,* **121**, 817(1955).

of abnormal homozygotes in the population is increased as the square root of the mutation rate. A gene that had had a frequency of 0.00010 would eventually build up to a frequency of 0.00014. With such small changes, it would seem unlikely that a doubling of the mutation rate could pose a serious problem to the life of the species, and it might go almost unnoticed. Some of our current dysgenic practices that are countenanced because of custom, inertia, humanitarian practices, or foolishness are probably more serious to the species.

"Lest anyone misinterpret these deliberations as justification for rashness, some special warning should be given. The basic fact to remember at all times is that any irradiation is bad, and therefore irradiation should be used only if it can be assumed that the good will outweigh the bad. Certainly our descendants should be protected by our avoiding the irradiation of the gonads of any person until he is past the procreative age. Also, the society as a whole should be protected against a general increase in background irradiation. The existence of worse practices cannot be an excuse for perpetrating a bad one."

We shall, following most geneticists, assume that a doubling of the natural mutation rate will almost certainly lead to serious consequences. The value of the doubling dose is itself very uncertain; it may be as low as 3r, though a value about 10 times larger appears more likely. The global fallout dose is also uncertain but about 0.1r seems to be a reasonable estimate for the test explosions so far conducted. It, therefore, seems that the genetic harm already done to mankind from past test explosions is probably negligible; but in the light of the existing knowledge one cannot be entirely certain of this conclusion.[25]

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[25] It is extremely important that all unnecessary exposure to radiation—particularly, exposure of the gonads—is severely restricted and, wherever practicable, altogether eliminated. (For instance, men-

Radiation does cause genetic damage, we know, but we cannot at present assess with any certainty the level of this damage. However, with no less than the genetic heritage of the entire human race at stake which responsible person would care to gamble?

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tion may be made of self-illuminating dials of watches and instruments; self-luminous signboards; toys painted with self-luminous paints; self-illuminating toilet seats in rest rooms; X-ray machines used in shoe-fitting; soft X-rays from television sets).

In connection with modern health-services the exposure (sometimes indiscriminate) of a large portion of the population to X-rays used for diagnostic purposes is becoming quite a serious problem and has been treated in considerable detail in the UK Medical Research Council Report on '*The Hazards to Man of Nuclear and Allied Radiation*', (H.M.S.O., June 1956). It is estimated that in 1955 alone there were about 18 million X-ray examinations. The genetically significant dose (gonad dose) when averaged over the entire population in the UK is as large as 0.02 roentgen per year per person: it is about 22 per cent of the dose received from natural background radiation. [Note incidentally that in a straight X-ray chest-examination the dose received by the chest is about 0.15 r, but the dose to the reproductive organs is as small as 0.4 milliroentgen for male and 0.1 milliroentgen for female. R.W. Stanford *et al.*, *British Journal of Radiology*, **28**, 266(1955)].

CHAPTER VII

CONCLUSION

"Here then is the problem which we present to you, stark and dreadful and inescapable: Shall we put an end to the human race: Or shall mankind renounce war? People will not face this alternative because it is so difficult to abolish war. . . .

"There lies before us, if we choose, continual progress in happiness, knowledge and wisdom. Shall we, instead, choose death because we cannot forget our quarrels? We appeal, as human beings, to human beings: Remember your humanity, and forget the rest. If you can do so, the way lies open to a new paradise; if you cannot, there lies before you the risk of universal death."

—Albert Einstein*

In the preceding chapters we have attempted to give an account of the effects—blast, heat and radiological—of nuclear explosions. One thing that clearly stands out above everything else is that the range of destruction of high-yield nuclear weapons is truly colossal. The multiplication factor, in comparison to the devastation caused by conventional weapons, is so big that it becomes extremely difficult to appreciate and assess the seriousness and peril of the new situation. Think of a 20 megaton bomb. It releases energy which is of the same order as that of a large earthquake or a hurricane: Its energy is equal to 2 percent of the total annual output of electrical energy in the world. If this bomb were to be made from conventional explosives, the mere cost of the explosives would be roughly thousand million pounds sterling. In terms of destructive power a nuclear weapon is the cheapest thing the world has ever seen—cheaper than conventional weapons by a factor of hundreds, if not thousands. The target that matches this weapon is a huge city : One single weapon by its blast effect alone would be good enough to destroy completely any metropolis. By sheer logic of the situation, megatons bombs and cities cannot co-exist for a long time. In all history the size of political units has, to a large extent, been influenced by the striking power and range of the weapons of destruction. The range of destruction of the nuclear weapons is such that inevitably, as Einstein put it, it must be one world or none. All seem to be agreed that war with nuclear weapons will not end in victors and vanquished, but it can only end in the end of civilization itself.

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* Extract from a statement issued in July 1955 under the signatures of Albert Einstein, Percy W. Bridgman, Leopold Infeld, Herman J. Muller, Cecil F. Powell, Joseph Rotblat, Bertrand Russell, Hideki Yukawa and Jean Fréderic Joliot-Curie. [*Science*, **122,** 189 (1955)].

We now come to nuclear test explosions which have been and are still being conducted to test new principles and techniques of nuclear weapons. In connection with these explosions there are two points which we have examined in some detail :

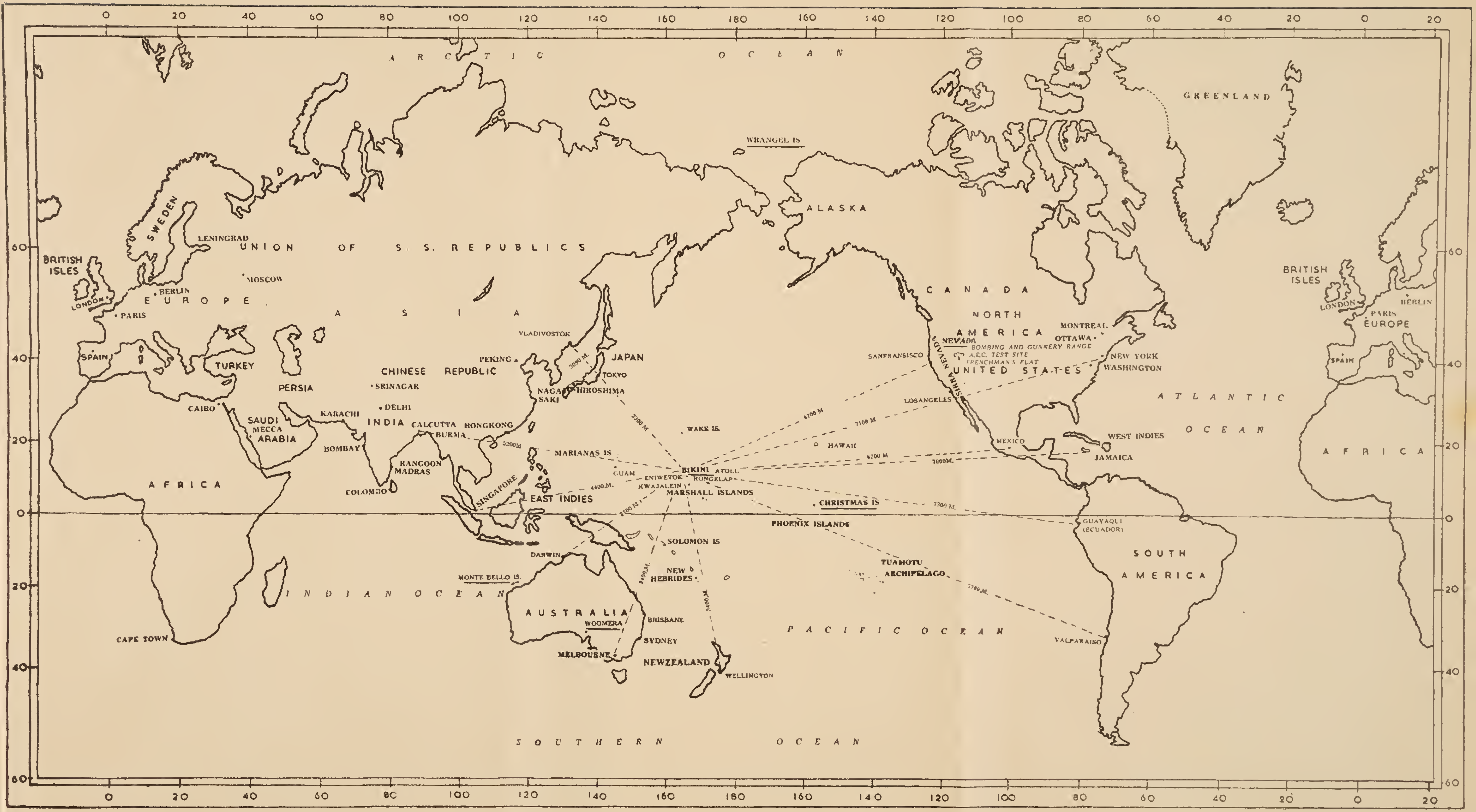
(i) the internal hazard resulting from ingestion (entry into and absorption in the body) of radioactive substances contained in the fallout from test explosions, the most serious component being radiostrontium,

(ii) the genetic hazard from exposure of the entire world population to ionizing radiation from global fallout.

All are agreed that the test explosions do cause harmful effects. What people are not generally agreed about is the magnitude of the harm resulting from them. This question of the actual scale of harm (resulting from test explosions) has, unfortunately, been mixed up with non-scientific and political issues. The scientific knowledge presently available is not enough to give a reasonably clear-cut answer. The assumptions that are made about the permissible radiation burden—somatic and genetic—that an average individual can carry without untoward effects, generally tend to be too optimistic. We have examined this point in some detail in Chapters V and VI. (For instance, the value usually adopted for strontium 90 seems to be certainly on the high side). Again, as global fallout is uniform all over the world, it is very likely that the first manifestation of its somatic ill-effects would occur in densely populous communities which have a comparatively low standard of nutrition and health. The same is true of the genetic hazard also. Here the knowledge of relevant factors is so uncertain that any conclusion as to the permissible level of exposure may be in error by a very big factor (even as large as 100). Further, it is very unlikely that the relevant basic knowledge will be available in the near future. This limitation is inherent in the very nature of the subject. It is extremely important that in the meantime (while we are still ignorant as to the true scale of hazard) the radiation exposure is kept down to the lowest possible value; otherwise irretrievable harm may be done to what is literally the most precious treasure of mankind, the genetic heritage.

While no one with any understanding of problems of nuclear war has argued that a war with nuclear weapons would be anything less than a total disaster, there are some people who argue that tests can continue, because it is not yet firmly established that, on the present scale, they would lead to any substantial increase in the existing somatic and genetic load of mankind. In effect, this means that tests can continue so long as it is not known with *certainty* that they would cause serious harm to man. This is a rather strange line of argument. To argue that tests should stop only if it were definitely established that their continuation would bring *certain* disaster to mankind, is a regrettable commentary on 2,500 years of progress since the

Buddha. In fact, there can be no doubt at all that if civilization is to endure and progress what is now necessary — and desperately so — is that the new knowledge of the atom instead of being mobilized for weapons and war, should be mobilized in the cause of peace and plenty.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